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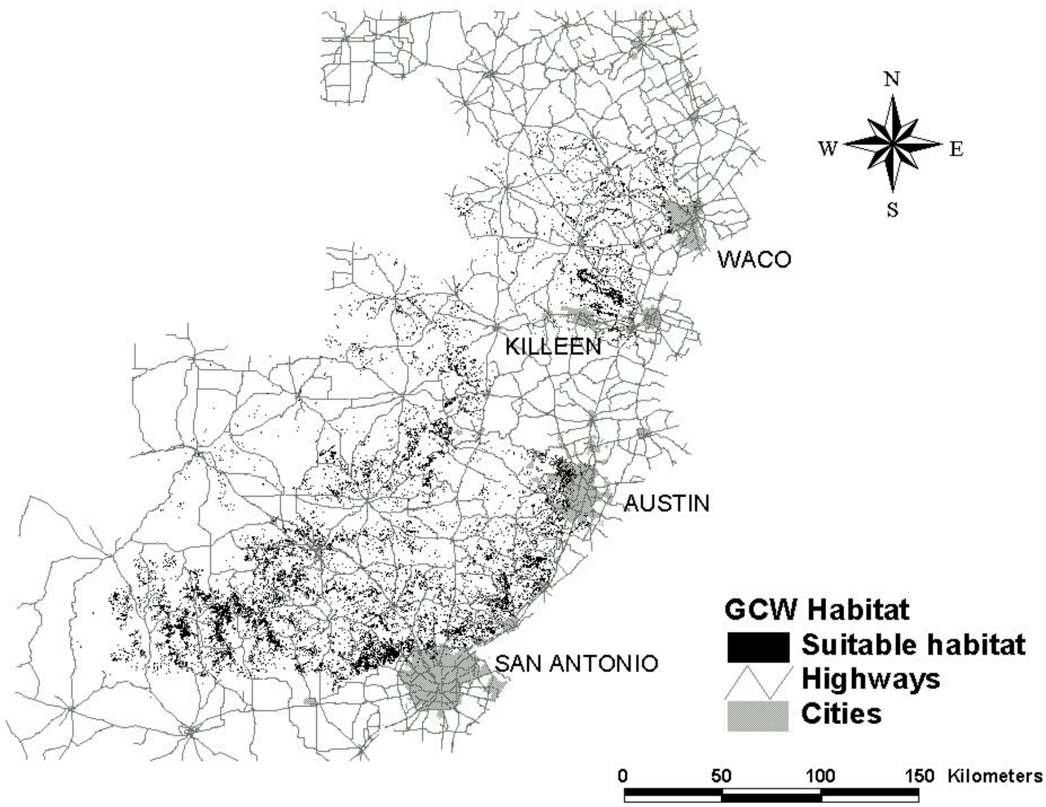
Construction Engineering Research Laboratory

US Army Corps of Engineers®
Engineer Research and Development Center

Evaluation of Models To Support Habitat Fragmentation Analysis

H. Resit Akçakaya, Kelly Cantara, Heather Vaillant, David Diamond, Diane True, Chris C. Rewerts, and Robert Lozar

July 2006



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Construction Engineering Research Laboratory
PO Box 9005
Champaign, IL 61826-9005

Final Report

Prepared for U.S. Army Corps of Engineers
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ABSTRACT: Although Army lands must primarily support troop training, the Army is also required to manage its training lands to meet other objectives, e.g., maintaining threatened and endangered species (TES) habitat. Because military training is more compatible with TES habitats than are commercial and residential land uses, military land has increasing value for habitat conservation and preservation. By itself, land on military installations is insufficient to ensure populations' long-term viability. Primary TES habitat must remain genetically connected with off-installation areas. A number of tools, "fragmentation models," which quantify the effect of habitat fragmentation on the persistence of threatened and endangered species, promise to help address the challenge of encroachment upon, and increasing need for training lands. This work reviewed a number of habitat fragmentation models and performed an in-depth investigation of one application at Fort Hood TX. This review evaluated and identified the relative strengths and weaknesses of landscape scale TES habitat fragmentation models as they relate to military installations within the continental United States.

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Conversion Factors

Non-SI* units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	0.00001638706	cubic meters
degrees (angle)	0.01745329	radians
degrees Fahrenheit	(5/9) x (°F – 32)	degrees Celsius
degrees Fahrenheit	(5/9) x (°F – 32) + 273.15.	kelvins
feet	0.3048	meters
gallons (U.S. liquid)	0.003785412	cubic meters
horsepower (550 ft-lb force per second)	745.6999	watts
inches	0.0254	meters
kips per square foot	47.88026	kilopascals
kips per square inch	6.894757	megapascals
miles (U.S. statute)	1.609347	kilometers
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
square feet	0.09290304	square meters
square miles	2,589,998	square meters
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms
yards	0.9144	meters

***Système International d'Unités* ("International System of Measurement"), commonly known as the "metric system."

Preface

This study was conducted for Engineer Research and Development Center, Construction Engineering Research Laboratory (ERDC-CERL), under Project 4A162720A896, “Environmental Quality Technology”; Work Unit CNN-T602FF, “Quantify Effects of Fragmentation and Approaches To Mitigate.” The technical monitor was Dr. William Severinghaus, Technical Director, and Military Lands Management Division.

The Ecological Processes Branch (CN-N) of the Installations Division (CN), Construction Engineering Research Laboratory (CERL), performed the work. The CERL Principal Investigator was Robert C. Lozar. Alan B. Anderson is Chief, CEERD-CN-N, and John T. Bandy is Chief, CEERD-CN. The associated Technical Director is Dr. William D. Severinghaus, CEERD-CV-T. The Acting Director of CERL is Dr. Ilker K. Adiguzel.

CERL is an element of the U.S. Army Engineer Research and Development Center (ERDC), U.S. Army Corps of Engineers. The Commander and Executive Director of ERDC is COL Richard B. Jenkins, and the Director of ERDC is Dr. James R. Houston.

1 Introduction

Background

Army lands must support troop training to optimize a soldier's battlefield success and survivability. Soldiers must train continually and under realistic conditions to keep skills fresh. Emerging weapon systems, new tactics, and inter-service training requirements demand more extensive tracts of land than ever before to properly train the forces. However, Federal, state, and local laws require the Army to manage its training lands to simultaneously meet other objectives, e.g., maintaining threatened and endangered species (TES) habitat. Fulfilling these sometimes competing goals can threaten the optimal use of military lands. The problem can be further complicated by urban development near installations, which destroys neighboring areas with habitat suitable to support TES populations.

Army training lands were often originally placed in remote areas where installations could easily meet their needs while avoiding potential conflicts with surrounding land use. Installation property boundaries delineated where people were not allowed to trespass, even though the actual impact of military activities (dust, smoke, noise and radio interference) may extend well beyond the property lines. Property boundaries do not impact the use of landscapes by plants and animals. Habitat patterns and mosaics continue to evolve through natural succession and disturbance processes, which included fire, disease, and insect invasions. Although the occupation of a specific piece of land by plant and animal species would change over time, the overall texture of broad landscapes allows populations of animals and plants to persist over tens of thousands of years in North America landscapes. In this ever-changing matrix of habitats, populations of plants and animals may be destroyed by various natural disasters, and then easily repopulate areas progressing through the steps of habitat succession.

Human settlement patterns (urban development) have dramatically changed the landscape such that native species do not (and cannot) reclaim their habitat. This affects remaining natural areas in two important ways. First, urban development reduces the amount of available natural habitat — decreasing the total carrying capacity for certain species and making smaller populations more susceptible to extinction. Second, urban development fragments (disconnects) the remaining habitat. That is, animals and propagules from plants from remaining good habitats

cannot reach other populations through migration or dispersion of plant pollens and seeds. The “islands” of remaining habitat lose their genetic connectivity; this phenomenon is called “habitat fragmentation.” Certain animals’ behaviors and habitat requirements, and some plants’ seed and pollen dispersal approaches may tolerate habitat fragmentation better than others. A given landscape may be fragmented for one organism, but not for another. Patterns of fragmentation can also differ. The loss of genetic connectivity will eventually result in the loss of genetic diversity in sub-populations, making the populations more susceptible to disasters and increasing the probability of local extinction.

The loss of habitat and connections among habitats to support genetic exchange increases the value of remaining habitat. Because military training is far more compatible with TES habitats, the value of military land for the conservation and preservation of these habitats continues to increase. In most cases, land on military installations is, by itself, insufficient to ensure populations’ long-term viability. Areas of primary habitat for threatened species on installations must remain genetically connected and these areas must also remain connected to other off-installation areas. That is, habitats must not become so fragmented that small populations become isolated. This need has resulted in the loss of installations land to training.

A number of tools (i.e., “fragmentation models”) that quantify the effect of habitat fragmentation on the persistence of threatened and endangered species, promise to help address the double challenge: of encroachment upon, and increasing need for training lands. This work reviewed a number of habitat fragmentation models and performed an in-depth investigation of one application for the region surrounding Fort Hood TX. This review was undertaken to evaluate and identify the relative strengths and weaknesses of landscape scale TES habitat fragmentation models as they relate to military installations within the United States.

Objective

The objectives of this work were to:

1. Review, test, and evaluate habitat fragmentation models and to make recommendations for the future development and application of models for evaluating fragmentation effects on threatened and endangered species
2. Provide installation land managers with an initial source reference document that reviews habitat fragmentation issues, focusing on those of highest concern to Army Military Installation Land Managers, including approaches to identifying appropriate land for protection under the Army Compatible Use Buffer (ACUB) program.

Approach

This work reviewed six habitat fragmentation models to evaluate and identify the relative strengths and weaknesses of the state of the art landscape scale TES habitat fragmentation models as they relate to military installations within the United States: FragStats, Patch Analyst, HAMS, HSI, RAMAS GIS, and EAM. An in-depth investigation was also performed of one application at Fort Hood TX. Each model was evaluated as follows:

1. If possible, the model was obtained. Each model was reviewed for source, purpose, input, output, required resources, technical expertise required, versatility, linkage ability, strengths, and shortcomings. A literature search was done on each model to generally evaluate the model for how it has been used, and for users reactions.
2. Models that were obtained and that would run on the computer systems available to the researchers were tested. Tests involved obtaining spatial data for two study sites for which U.S. Army Corps of Engineers provided spatial data in the form of raster (grid) files:
   a. an area approximately 43,904 km^2 surrounding Fort Bragg, NC
   b. approximately 94,211 km^2 in the vicinity of Fort Stewart, GA.

   Models requiring species' habitat preferences used the Red-cockaded woodpecker, *Picoides borealis*, as the "study species." This species was selected because it is on the list of species critical to Army installations, and because data on this species were readily available.

After review and testing, all models were evaluated and recommendations were formulated for future application and development of models for evaluating fragmentation effects on threatened and endangered species.

Scope

This work primarily focused on initiatives with relevance to military installation conditions, with an emphasis on the specific needs of Army land managers. This focus, combined with the nature of habitat fragmentation, required that study concentrate on regional scale landscape ecology.

Mode of Technology Transfer

This work will support further research to improve a military installation planner's ability to identify appropriate land near an installation that, if purchased, will re-

lieve threats of TES habitat fragmentation and thereby sustain future training and testing requirements and opportunities.

This report will be made accessible through the World Wide Web (WWW) at URL:
http://www.cecer.army.mil

2 Review of Models

FRAGSTATS (Version 3.0)

Source

McGarigal 2002
See also McGarigal and Marks 1995
Developer: Dr. Kevin McGarigal
Contact: mcgarigalk@forwild.umass.edu
Web Site: http://www.umass.edu/landeco/research/fragstats/fragstats.html
Use: Install

Overview

FragStats is a program designed for the spatial analysis of categorical maps. It quantifies the areal extent and spatial configuration of patches within a landscape that is defined and scaled by the user. Landscape metrics are then used to quantify patches on three levels: individual patches, classes of patches, or entire landscape mosaics. Landscape metrics fall into two categories, those that quantify the map composition without reference to spatial attributes, and those that quantify the spatial configuration of the map (described more fully below).

FragStats analyzes the spatial attributes of landscape patches, and is useful in describing habitat fragmentation. Results of FragStats simulations can be further analyzed with respect to threatened and endangered species (TES) in three ways:

1. By running a Principal Component Analysis (PCA) of the FragStat results, and regress PCA results against TES abundance/surveys (McGarigal and McComb 1995).
2. By using multiple regression analysis on the FragStats output metrics with TES survey data (Erickson and West 2003).
3. By incorporating the FragStats results into ArcView GIS for spatial modeling, using the spatial analyst tool (Bender et al. 2003).

Output

FragStats computes three groups of metrics, one for each patch in the mosaic, one for each class of patch in the mosaic, and one for the landscape mosaic as a whole.

In addition, an adjacency matrix is computed, which is a tally of the number of adjacencies between each pairwise combination of patch types. The adjacency matrix is used in the computation of several class and landscape level matrices.

Composition analysis of the landscape refers to features associated with variety and abundance of patch types within the landscape, without consideration of spatial character, placement, or location of patches within the mosaic. Measures of composition include proportional abundance of each class, richness (number of different patch types), evenness (relative abundance of each patch type), and diversity (composite measure of richness and evenness). Composition metrics can only be applied to the landscape level, as it requires integration over all patch types.

Spatial configuration analysis refers to the spatial character and arrangement, position, or orientation of patches within the class or landscape. Aggregation is across patches at the class or landscape level; spatial metrics quantified in terms of the individual patches are explicit only at the patch level. Spatial configuration that is quantified in terms of the spatial relationship of individual patches and patch types are spatially explicit at the class or landscape level only. Overall, spatial configuration metrics represent recognition that ecological processes and organisms are affected by the overall configuration of patches and patch types within the broader patch mosaic. The following are measures of spatial configuration:

- Patch size distribution and density.
- Patch shape complexity, the geometry of patches (simple and compact vs. irregular and convoluted).
- Core area, the interior area of patches after an edge-buffer (user specified) is eliminated. This is the area that is unaffected by edge effects.
- Isolation/proximity, the tendency for patches to be relatively isolated in space (distance) from other patches that are the same or similar.
- Contrast, the relative difference among patch types. Mature forest would have a low contrast with respect to young forest, but a high contrast with respect to open field.
- Dispersion, the tendency for patches to be regularly or contagiously distributed with respect to each other. This is most commonly analyzed with the nearest neighbor distances between patches of the same type.
- Contagion/Interspersion. Contagion is the tendency of patch types to be spatially aggregated, to occur in large, contagious distributions. It ignores patches per se, and measures extent to which the cells of a similar class are aggregated. Interspersion is the intermixing of patches of different types and is based entirely on patch (not cell) adjacencies.
- Subdivision, the degree to which a patch type is broken up into separate patches. In other words, the degree of fragmentation. It is not the size, shape, relative location or spatial arrangement of those patches, only the de-

gree to which the patch type is fragmented (when applied at the class level). At the landscape level, subdivision metrics show the graininess of the landscape.

- Connectivity, the functional connectiveness of the patches. Functional connections will vary depending on the application of interest. For example, connectivity will be different for an insect and a bird in the same landscape.

Table 1 lists the four file types that are output from FragStats. Table 2 lists sample FragStats model output. All files are comma-delimited ASCII files and can be formatted for spreadsheet and database analysis (Figures 1 and 2).

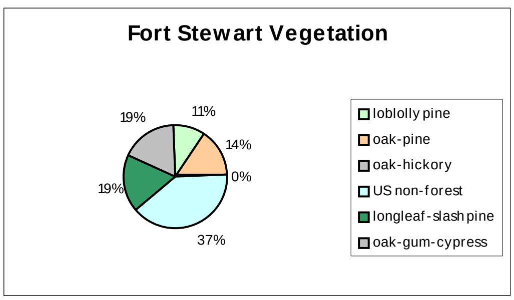
Table 1. "Fragstats" output file types.

File Type	Description
XXX.patch	Contains all patch metrics
XXX.class	Contains all class metrics
XXX.land	Contains all landscape metrics
XXX.adj	Contains the adjacency matrix

Table 2. Example of FragStats model output on the landscape scale. (Refer to Appendix for a complete description of the metrics listed.)

Landscape Level Metrics						
Metric	**Fort Bragg**	**Fort Stewart**	**Metric**	**Fort Bragg**	**Fort Stewart**	
TA	4390400	9421100	CONTIG_MN	0.1133	0.1364	
NP	4735	6875	CONTIG_AM	0.5831	0.6377	
PD	0.1078	0.073	CONTIG_MD	0	0	
LPI	22.63	25.46	CONTIG_RA	0.8144	0.846	
LSI	40.96	54.20	CONTIG_SD	0.1538	0.1716	
AREA_MN	909.27	1365.21	CONTIG_CV	135.74	125.83	
AREA_AM	311833.77	835674.48	PAFRAC	1.5857	1.577	
AREA_MD	100	100	ENN_MN	2758.83	2806.35	
AREA_RA	993300	2398300	ENN_AM	2140.04	2118.74	
AREA_SD	16814.12	33749.15	ENN_MD	2236.07	2236.07	
AREA_CV	1849.19	2472.09	ENN_RA	25513.63	110294.26	
SHAPE_MN	1.2039	1.2578	ENN_SD	1582.19	2441.20	
SHAPE_AM	9.241	13.01	ENN_CV	57.35	86.99	
SHAPE_MD	1	1	CONTAG	27.85	32.77	
SHAPE_RA	16.71	23.81	PLADJ	59.77	65.14	
SHAPE_SD	0.6618	0.7808	IJI	80.67	77.31	
SHAPE_CV	54.97	62.08	COHESION	96.14	97.65	
CORE_MN	909.27	1365.21	DIVISION	0.9303	0.9116	
CORE_AM	311833.77	835674.48	MESH	305796.54	832543.28	
CORE_MD	100	100	SPLIT	14.36	11.32	
CORE_RA	993300	2398300	PR	6	6	
CORE_SD	16814.12	33749.15	PRD	0.0001	0.0001	

Landscape Level Metrics						
Metric	Fort Bragg	Fort Stewart	Metric	Fort Bragg	Fort Stewart	
CORE_CV	1849.19	2472.09	RPR	66.67	66.67	
DCORE_MN	909.27	1365.21	SHDI	1.4353	1.5211	
DCORE_AM	311833.77	835674.48	SHEI	0.801	0.8489	
DCORE_MD	100	100	AI	60.35	65.59	
DCORE_RA	993300	2398300				
DCORE_SD	16814.12	33749.15				
DCORE_CV	1849.19	2472.09	Some Interesting (non-significant) Differences			
FRAC_MN	1.0203	1.0243	Metric	Bragg	Georgia	% Difference
FRAC_AM	1.1696	1.1907	PD	0.1078	0.073	32.28%
FRAC_MD	1	1	CONTAG	27.85	32.77	17.66%
FRAC_RA	0.2578	0.2798	SHDI	1.4353	1.5211	5.98%
FRAC_SD	0.0337	0.0368	SHEI	0.801	0.8489	5.98%
FRAC_CV	3.3037	3.5901				
PARA_MN	34.95	33.99	PD—patch density (# patches/100ha)			
PARA_AM	16.09	13.94	CONTAG—aggregation of patch types (%)			
PARA_MD	40	40	SHDI—Shannon's Diversity Index			
PARA_RA	32.87	34.18	SHEI—Shannon's Evenness Index			
PARA_SD	7.02	7.69				
PARA_CV	20.08	22.64				



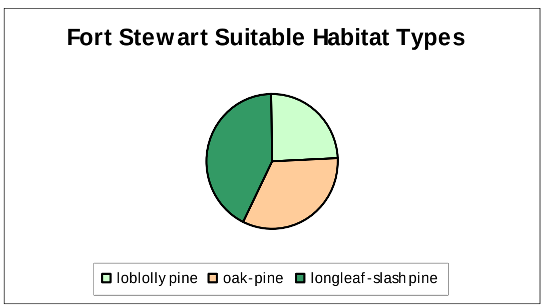
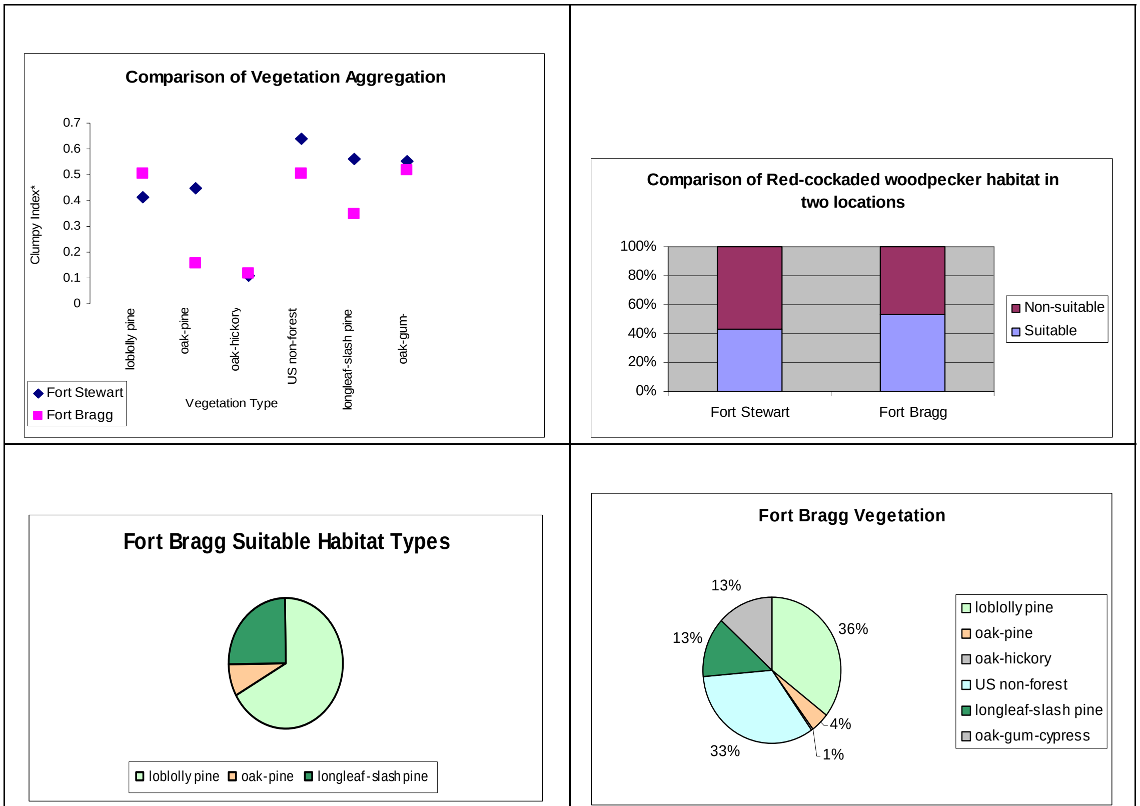


Figure 1. Plots showing the vegetation coverage near Fort Bragg, NC and Fort Stewart, GA.

Input

FragStats can accept data in several raster formats, including ArcGrid, ASCII, BINARY, ERDAS, and IDRISI image files. FragStats does not accept Arc/Info vector coverages (Version 2.0 did). Data input into FragStats must conform to certain specifications, and each data type has additional limitations (Table 3).

First, all input grids should be signed integer grids with non-zero class values. All input grids should consist of square cells with a cell size specified in meters.



*Clumpy index indicates the amount of aggregation in the landscape. Results indicate that the land is slightly to moderately aggregated in both locations. This and other metrics indicate that there is no significant difference between locations with respect to fragmentation

Figure 2. Plots generated using FragStats metric outputs.

Table 3. "FragStats" input file types and specifications.

Data Format	Specifications	Limitations
ASCII	Cells assumed to be square User must enter cell size in meters No header Each record contains 1 image row Cell values separated by comma or space	
32-bit BINARY	Cells assumed to be square User must enter cell size in meters No header	
16-bit BINARY	Cells assumed to be square User must enter cell size in meters No header	Patch ID in signed 32-bit integer format Moving window in 32-bit floating-point grids
8-bit BINARY	Cells assumed to be square User must enter cell size in meters No header	Patch ID in signed 32-bit integer format Moving window in 32-bit floating-point grids
ERDAS (version 7)	Projection/header information must be specified (defines cell size) Accepts *.gis and *.lan files, which are limited to unsigned 8- or 16-bit grids	FragStats rejects multi-layer files

Data Format	Specifications	Limitations
ERDAS (version 8)	Projection/header information must be specified (defines cell size) Accepts *.gis, *.lan, *.img files in signed 8-, 16- and 32-bit grids	Patch ID in signed 32-bit integer format Moving window in 32-bit floating-point grids
IDRISI	Projection/header information must be specified (defines cell size) Supports signed 8- or 16-bit integers and 32-bit floating point grids	Limitations on the # of patch types (limitations usually beyond study scope)
ArcGrid	ArcView Spatial Analyst or ArcGIS must be installed	FragStats must have access to a certain *.dll file in Bin32 directory

In addition to specifications and limitations on each data type, there are also limitations when working with raster images. Raster images are constrained by lattice grid structure. Therefore, raster images portray lines in stair-step fashion, resulting in an upward bias in edge length measurement. The magnitude of this bias depends on cell size of the image, and consequences must be weighed relative to the specific study. If necessary, one can convert a vector coverage into a raster image for use in FragStats. However, it can cause problems if the cell size chosen is too large, resulting in numerous 1-cell patches. To avoid this problem, a cell size less than ½ the narrowest dimension of the smallest patches is needed.

Resources Required

FragStats was tested and run on Windows NT and 2000 systems. (It is compatible with other Windows versions.) The program is computer-intensive; performance relies on both processor speed and computer memory (RAM). The speed of processing an image is dependent on processor speed, while the ability of FragStats to process an image is dependent on having sufficient memory (up to 1.14Gb of RAM for a 10,000 x 10,000 grid).

To use FragStats for a TES assessment, one must have ArcView GIS for display, a spreadsheet program (Excel), and a statistical program (SAS, SPSS) for analysis.

Technical Expertise Required

To import data into FragStats, one must be familiar with any one or combination of the following data formats/programs: ASCII, BINARY, ArcGrid, ERDAS, or IRDISI. The data must be in raster form, which the user must be familiar with.

One can also execute FragStats from another program via command line, in which the syntax call *FragstatsParameterizationFile.frc/c* must be used. If the FragStats

program is not in the same folder, one must then specify the full path name to execute (*Drive:\path_to_Fragstats\ FragstatsParameterizationFile.frc/c*), as follows:

- *ParameterizationFile* is the name of the FragStats parameterization file created using the standard FragStats graphical user interface. It specifies all required and user-selected parameters of the analysis. The extension *.frg is assigned to parameterization files in FragStats.
- /c is a switch that closes FragStats after execution of the program.

To analyze the effects of habitat fragmentation on a species, one must be familiar with PCA methods, statistical methods (such as regression and data transformation), and/or ArcView GIS (with spatial analyst).

Support

Technical support for FragStats is available through URL:
http://www.umass.edu/landeco/research/fragstats/fragstats.html

One may also e-mail the developer, Dr. Kevin McGarigal, at:
mcgarigalk@forwild.umass.edu

Versatility

FragStats is used strictly for landscape assessment, primarily the assessment of habitat fragmentation in a study area. It can be used in a variety of different habitat types (woodland, prairie, tropical forest, etc.), but cannot be used in analysis of any species. The output data from FragStats can be used in a PCA Analysis, regression analysis, or incorporated into ArcView GIS for use with faunal species analysis.

Linkage Ability

FragStats is able to input a variety of data formats, including ASCII, BINARY, ERDAS, IDIRIS, and ArcGrid. Data must be in raster format, and further limitations apply to each format (see above). The output data is in ACSII format, and is easily imported into other programs for database management and further analysis.

Strengths

FragStats analyzes the extent and spatial configuration of patches within a landscape using metrics. These metrics are very well defined and specific. FragStats is therefore an extremely thorough tool for analyzing landscape structure, particularly habitat fragmentation.

Shortcomings

There are four primary shortcomings of FragStats as a tool for analyzing the effects of habitat fragmentation, which apply to any program that analyzes landscape structure, including r.le and Patch Analyst:

1. FragStats analysis is based on pre-defined patches or habitat categories. To be useful in habitat fragmentation assessment, the definition, and the spatial scale of patches must be determined for a particular species before the analysis. This would require a habitat analysis for the species, and considerations of behavioral characteristics of the species (territoriality, home range, dispersal, etc.) that affect its use of space. These must be determine before an analysis by FragStats is carried out. As mentioned in previous chapters, connecting the biology of a TES to analysis packages available is the problem. Therefore, a good many of these questions must be answered before FragStats is applied.
2. FragStats is designed to analyze the extent and spatial configuration of patches within a landscape, and is not able to analyze the effects of habitat structure on floral or faunal species. That must be done using PCA, regression, or ArcView GIS methods. This would require determining the biological variable (such as abundance, survival, fecundity, etc.), and collecting spatially explicit data on this variable. Note too, that even analysis of species using these methods will only account for landscape metrics, and does not take into consideration variables such as food availability, microclimate, etc.
3. It is often difficult to interpret the results of FragStats for the purposes of predicting fragmentation impacts. The types of analysis described above can be used to find relationships between landscape metrics and population responses, but it is difficult, if not impossible to use these relationships for predictive purposes, e.g., to predict the future population responses in the same landscape, or the population responses in another landscape, or the response of another species. The reason for this is that there are no *general* relationships between landscape indices and the persistence of populations inhabiting the landscape. In specific cases, the relationships vary with species, with landscape, and with the spatial scale.
4. FragStats cannot analyze changes in patch or landscape dynamics, such as perforation, dissection, shrinkage, or attrition. Apan et al. (2002) and the section "Patch Analyst" (p 23) further comment on this function.

Applications

FragStats has been used in a number of empirical studies of habitat fragmentation and its effects on faunal populations. Studies have used FragStats in conjunction with PCA methods, regression analysis, and ArcView GIS mapping and analysis.

Table 4 lists the types of studies that have employed FragStats; three of these studies are summarized below.

Table 4. Studies that have used FragStats.

Plant	Invertebrate	Amphibian/ Reptile	Fish	Bird	Mammal
Zhao et al. 2003, Lofman and Kouki 2003, Axelsson and Ostlund 2001				Grand and Cushman 2003, Watson 2003, McGarigal and McComb 1995	Erickson and West 2003, Woolf et al. 2002

The first study was performed along the Oregon Coast Range, to determine how changes in landscape structure affected bird populations (McGarigal and McComb 1995). The goal was to quantify the relationship between late-seral forest configuration and extent with the abundances of several bird species known to inhabit that forest type.

After all analysis was completed, the results showed that the relationship between late-seral forest and bird abundance varied greatly among species. Some species were unaffected by the forest area, while other species showed variation that could not be explained by habitat area alone. One trend that was observed, however, was that variation in abundance among landscapes was more strongly correlated with habitat area as opposed to habitat configuration.

In the next study, the authors sought to understand the distribution and activity patterns of bats, given habitat associations at multiple scales (Erickson and West 2003). Two scales were used, stand and landscape. FragStats was used on the landscape scale only. For the landscape analysis, digital vegetation cover was obtained for the study area in western Oregon and Washington states. Vegetation classification was summarized into four types: (1) clearings, clear-cuts, meadows, grasslands, and tree seedlings/saplings, (2) tree saplings/poles, (3) small trees 26-50cm dbh, and (4) medium and large trees >50cm dbh.

Unfortunately, there were no significant landscape effects found in this study. This could be due to the resolution of the spatial data used to generate the landscape metric in FragStats. Patches that were classified as homogeneous often contained several tree sizes and heights, as well as forest gaps. They could potentially provide bats with suitable habitat.

Even though no relationship was found between landscape patterns and bat activity, the two sites with unique landscape characteristics also had higher activity levels. This suggests that there are some landscape level factors associated with bat activity in the study area.

Patch isolation is the subject of the next article using FragStats (Bender et al. 2003). Patch isolation is a key component when predicting species distribution in spatially subdivided (i.e., fragmented) populations. The goal of the Bender study was to determine which isolation metric(s) provided the most reliable measure of patch isolation as it relates to organism dispersal. In addition, the study looked at the usefulness of isolation in predictions of animal movement in different landscape types. The distinction was made here between isolation (configuration) effects and patch character (size/shape) effects.

Although patch size and shape, which are not isolation metrics, accounted for about ½ of the variation in immigration rate, over ⅓ of the variation in immigration rate was accounted for by isolation metrics alone.

The conclusions of this paper were that area-informed isolation metrics (in this case buffer and proximity indices) were much better predictors of immigration than were distance-informed isolation metrics (Voronoi polygons and nearest neighbor). Area-informed metrics also performed well in both landscape types, and are therefore the most reliable and robust metrics across various landscape spatial patterns.

FRAGSTAST*ARC

FragStats*ARC is a standalone ArcInfo or ArcView application used for quantifying landscape structure through spatial pattern analysis. The program contains all of the metrics found in FragStats, as well as additional metrics such as total edge, edge density, landscape shape index, nearest neighbor polygon identifier, and interspersion and juxtaposition. FragStats*ARC is capable of:

- managing ArcInfo coverages and data sets
- manipulating and pre-processing ArcInfo data for use with FragStats
- executing FragStats through an intuitive wizard interface that will automatically prompt you for data parameters and input requirements
- managing FragStats runs using a meta-data interface
- querying and displaying FragStats output tables with transparent linkages to input ArcInfo coverages
- exporting map, graphic and report outputs to other formats (not specified) for integration with word processing or other programs.

FragStats*ARC has several advantages over the public domain FragStats program discussed above. They include:

- *Integration*. FragStats*ARC integrates seamlessly into ArcInfo, operating as an application of that program.

- *Performance*. Calculations are done directly on linked data tables, taking only minutes (where FragStats takes hours to complete).
- *Flexibility and Extendibility*. FragStats*ARC supports existing vector indices and raster indices in one version. FragStats requires two versions, one for vector and one for raster indices.
- *Data Management*. Users can refer to input and output data without having to know internal file names, etc.

FragStats*ARC version 3.2 is capable of use within ArcInfo or ArcView GIS.

R.LE. (Raster Landscape Ecological) Model

Source

Baker 2001

Developer:	William L. Baker
Contact:	BAKERWL@UWYO.EDU
Phone:	(307) 766-2925
Web site:	http://www3.baylor.edu/grass/gdp/landscape/r_le_manual5.pdf
Use:	Install r.le and GRASS

Overview

The raster landscape ecological (r.le) programs (formerly known as GLE programs) were designed to analyze the structure of nearly any landscape by calculating a variety of common quantitative measures of landscape structure. These programs are very similar to the FragStats program (see above), and are used for the same purpose.

The r.le programs were designed for analyzing landscapes composed of a mosaic of patches. More generally, they are capable of analyzing any 2-D raster or array whose entries are integer or floating-point values. Analysis can be done on multiple scales that the user may specify prior to analysis. Calculations that result from r.le programs are single value output calculations, such as mean patch size in a sampling area, as well as measures that produce a distribution of values as output, such as a frequency distribution of patch sizes in the sampling area. It is also possible to output tables of data about selected attributes of individual patches.

The r.le programs are intended to be part of the Geographical Resources Analysis Support System (GRASS), a public domain geographical information system (GIS) supported by a worldwide network of developers and users.

For TES analysis, one must use PCA, regression, or Spatial Analyst (ArcView GIS) methods, as described above for FragStats.

Output

The r.le analysis programs include r.le.dist, r.le.patch, and r.le.pixel. Each is designed to perform landscape ecological analysis by computing the spatial measures selected from the measure list available from each program.

The r.le.dist program is used to measure distances between patches and to report those distances using several methods. Table 5 lists the distance measures one can compute.

Table 5. The r.le dist program output.

Method/ Measure	Scale/Sample	Description of Analysis
di1 (method)	From each patch to all adjacent neighbors of patch	Center-center distance Center-edge distance
	From each patch to the nearest patch of the same group	Center-center distance Center-edge distance Edge-edge distance
	From each patch to the nearest patch of different group	Center-center distance Center-edge distance
	From each patch of a specific group to the nearest patch of a specific group	Center-center distance Center-edge distance Edge-edge distance
di2 (measure)		Mean distance with standard deviation Mean distance by group with standard deviation Number of distances by distance class Number of distances by distance class group

The r.le.patch program is used to calculate attribute, patch size, core (interior) size, shape, boundary complexity, and perimeter measures for sets of patches in a landscape. Table 6 lists attribute measures for the r.le.patch program.

Table 6. The r.le.patch program output.

Parameter	**Method/Measure**	**Description**
att (attribute)	Mean pixel with standard deviation	Average value and standard deviation of the attributes of all non-null cells in the sampling area
	Mean patch with standard deviation	Average attribute and standard deviation of all patches in the sample area
	Cover by group	Measure of the amount of land area covered by each group
	Density by group	Measure of the number of patches in each group
	Total density	Measure of the raw total number of patches in sample area
	Effective mesh number (Splitting index)	Number of patches one gets when dividing the region into parts of equal size in such a way that the new configuration leads to the same degree of landscape division Jaeger 2000
siz (size)	Mean patch size with standard deviation	Mean size or area (in cells) of patches in sample area
	Number by size class	Measure of the number of patches in sampling area that fall within each size class
	Number by size class by group	Measure of number of patches that fall within each class size, calculated separately for all patches within each group
	Effective mesh size	Denotes the size of areas when the sample area is divided into S areas with the same degree of landscape division Jaeger 2000
	Degree of landscape division	Probability that two randomly chosen places in a landscape are not situated in the same un-dissected area Jaeger 2000
co1	Width of edge in cells (for use with *co2*)	Represents how wide the area of the patch is that is suspected to be affected by patch edge
Parameter	Method/Measure	Description
co2 (core size)	Mean core size with standard deviation	Mean size or area of the core of patches in landscape, calculated for all patches (core/no core)
	Number of cores and edges by size class by group	Number of cores and edges of patches in landscape that fall within each size class, calculated separately for all cores and edges within each group
sh1 (shape indices)	Perimeter/area	Total length of perimeter of each patch is calculated, divided by its area, and the mean of these values is then calculated
	Corrected perimeter/area	Corrects for a size problem in above calculation
	Related circumscribing circle	Index to compare the area of the patch to the area of the smallest circle that can circumscribe the patch
sh2 (shape measures)	Mean patch shape with standard deviation	Calculated for all patches in landscape, ignoring the group of each patch
	Mean patch shape by group with standard deviation	Mean patch shape within landscape, calculated separately for all patches within each group
	Number by shape index class	Number of patches whose shape index value falls within each shape index class

Parameter	Method/Measure	Description
	Number by shape index class by group	Number of patch whose shape index value falls within the shape index class, calculated separately for all patches in each group
bnd (boundary complexity)	Mean twist number with standard deviation	Based on count of the number of straight segments along boundary of patch (large value associated with small segment lengths and rough perimeters)
	Mean omega index (Ω) with standard deviation	Index of irregularity of patch perimeter based on the twist number (high values associated with straight perimeter segments)
per (perimeter)	Sum of perimeters	Total of all perimeter for all patches, ignores group
	Mean perimeter with standard deviation	Mean perimeter length for all patches, ignoring group
	Sum of perimeters by group	Total of all perimeters for all patches, calculated separately for each group
	Mean perimeter by group with standard deviation	Mean perimeter length calculated separately for all patches in each group

The r.le.pixel program contains a set of measures for attributes, diversity, texture, juxtaposition and edge. Table 7 lists this program's various calculations output.

Table 7. r.le.pixel program output.

Parameter	Method/Measure	Description
att (attribute)	Mean pixel attribute with standard deviation	Average value of the attributes of all non-null cells in sampling area
	Minimum pixel attribute	Smallest non-null pixel attribute
	Maximum pixel attribute	Largest non-null pixel attribute
div (diversity)	Richness	Number of different patch attributes in landscape
	Shannon index (H')	Index that combines richness and evenness
	Dominance	Index related to Shannon index, but emphasizes deviation from evenness
	Inverse Simpson's index (1/S)	Combines richness and evenness; measures probability of encountering two cells of the same attribute in a random sample of two cells
te1(adjacency)		Seven measures to analyze adjacencies for each cell
te2(texture)	Contagion	Quantifies the degree of clumping
	Angular second moment (energy)	Measure of textural uniformity, i.e., pixel pairs repetitions
	Entropy	Entropy is a maximum with completely random gray-level values from window-window (complete disorder)
edg (length of patch boundary)	Sum of the edges	Total length of all edges, counted only once, of all patches in a landscape (different from total perimeter in that this measure only counts edges once, while parameter counts each twice)
	Sum of edges by group	Length of all edges of a particular type (type specified by user)

In addition to the three r.le programs above, r.le.trace is a quick method for getting basic information about a particular patch or set of patches, including area and perimeter. When sampling the whole map in GRASS, r.le.trace can do three things: (1) show patch numbers on the display, (2) display the attribute, area, perimeter, shape indices and twist indices for each patch, and (3) save these data in an output file.

Input

The r.le programs work directly with map layers that have been put and preprocessed in GRASS (Table 8). Preprocessing functions include rectifying imagery to match a planimetric map, or classifying raw multi-band data. Data from satellites can be downloaded into GRASS using its image processing programs. GRASS also has programs for reading files produced by ERDAS, Arc/Info, ASCII raster files, TIFF files, Sun raster files, and several other formats. Vector information can be input using GRASS digitizing programs or from other GIS programs, but must be converted to raster data prior to using the r.le programs.

To run the r.le programs, one must first start GRASS and set up the working environment in GRASS, by specifying the GRASS location and map layers to be used. Usually, the sequence of operations is to use the r.le.setup to set up a sampling framework (regions, sampling area size and shape, scales, etc.) and then use the other r.le programs to make desired measurements. If the analysis will be the full extent of the GRASS region, one does not need to run the r.le.setup program.

Resources Required

The r.le programs are intended to be a part of GRASS, a public domain GIS. GRASS operates under several versions of the UNIX operating system, under LINUX, and Windows running Cygwin (experimental and there are problems with the r.le interface).

Table 8. r.le input file types.

Raster: ASCII, ARC/GRID, E00, GIF, GMT, TIF, PNG, ERDAS LAN, Vis5D, SURFER (.grd)... Using GDAL library (r.in.gdal) more formats like CEOS (SAR, LANDSAT7 etc.) can be read	**Image (satellite and air-photo):** AVHRR, BIL/BSQ, ERDAS LAN, HDF, LANDSAT TM/MSS, NHAP aerial photos, SAR, SPOT, …
Vector: ASCII, ARC/INFO ungenerate, ARC/INFO E00, ArcView SHAPE (with topology correction), BIL, DLG (U.S.), DXF, DXF3D, GMT, GPS-ASCII, USGS-DEM, IDRISI, MOSS, MapInfo MIF, TIGER, VRML,	**Sites (point data lists):** XYZ ASCII, dBase

r.le programs do not run statistical tests, nor are there graphing options. External software must be used to obtain statistical and graphical information. The program was written in the C programming language.

Technical expertise required

To use the r.le programs, one must be familiar with the GRASS GIS program and any programs used to pre-format the data for TES characterization.

To analyze the effects of habitat fragmentation on a species, one must be familiar PCA methods, statistical methods (such as regression and data transformation), and/or ArcView GIS (with spatial analyst).

Support

Support for the GRASS program is accessible via the GRASS web site, at URL:

http://www.geog.uni-hannover.de/grass.

Support for the r.le programs can be obtained through the program developer, William Baker, at e-mail:

BAKERWL@UWYO.EDU

Versatility

The r.le programs are designed strictly for landscape assessment, through calculations of quantitative measures. They can be used to assess the structure of nearly any landscape. However, r.le programs do not analyze impact to a faunal species. Output data from r.le programs can be analyzed using PCA methods, regression analysis, or GRASS GIS for statistical and graphical representation. The same methods can be used to assess species' impacts.

Linkage ability

The r.le programs are able to use a variety of data formats through the GRASS program, including ERDAS, Arc/Info, ASCII raster files, TIFF files, Sun raster files, and several other formats. GRASS is able to convert vector formats to raster formats for use in r.le programs. Calculations or landscape structure performed in r.le programs are given in ASCII format, and may then be easily imported to other programs for statistical analysis and other uses.

Strengths

Although r.le does not have all of the features of FragStats, it is still a very good tool for landscape analysis. The program offers a flexible sampling overlay system that is useful in analyzing irregular land areas or in obtaining a sample. Users of r.le can distribute sampling areas over a part of the landscape, calculate indices for separate, irregularly shaped regions, or sample only in the vicinity of point (wildlife) observations. FragStats operates only on a rectangular land area input into the program.

One other strength of r.le programs is that they are able to evaluate the landscape on up to 15 different scales simultaneously, specified by the user. FragStats evaluates the landscape on only three scales, patch, class, and landscape.

In addition, r.le can accept a wide variety of raster data formats, as well as vector formats. Vector formats are converted to raster formats for analysis in the GRASS program. Finally, the GRASS program allows users to analyze, store, update, model and display data quickly and easily. Other landscape programs, such as FragStats, must export data to ArcView GIS or some other program prior to display, as the only output is an ASCII file. R.le files, because they work in GRASS GIS systems, do not have to be exported for display of results.

Shortcomings

As in FragStats, r.le programs only analyze landscape structure. The four primary shortcomings discussed under FragStats also apply to r.le.

There are some major differences between r.le programs and FragStats. First, r.le programs do not have as rich an array of core area metrics. It does not have the proximity metric, nor does it contain any feature for dealing with patches on the edge of a map.

Finally, the r.le programs use the public domain GRASS program, which has several bugs. Also, some features of the GRASS program are not well documented (EPA 2000).

Applications

The r.le programs have been used in a variety of empirical studies, including landscape analysis of species' habitat and restoration of landscape structure following disturbance. The following table demonstrates the types of studies using r.le programs; three of those studies are summarized below.

Table 9. Studies that have used r.le programs.

Plant	Invertebrate	Amphibian/ Reptile	Fish	Bird	Mammal
Baker 1992, Baker 1994, Pogue and Schnell 2001					Ortega-Huerta and Medley 1999

The first two studies were performed by the developer of the r.le programs Baker 1992, 1994. Both studies used the r.le programs to analyze landscape structure following disturbance in the Boundary Waters Canoe Area (BWCA) in northern Minnesota.

In 1992, Baker used a GIS model derived from the DISPATCH model to assess the effects of settlement and fire suppression on landscape structure. Incorporated into that model were four major components: (1) a disturbance generator written in SIMSCRIPT II.5, (2) spatial data on patch ages maintained in GRASS, (3) r.le programs (formerly called GLE programs), and (4) external statistical and graphical analysis. The r.le programs were used to calculate indices of landscape structure, which were given threshold values to indicate significant changes in landscape.

Results of this study showed that the rapidity of change in the structure of disturbed landscapes might depend on several factors of the disturbance, including magnitude, character and direction of alteration. It also depends on the characteristics of the landscape within which changes occur. Finally, they concluded that the dynamics of a population of disturbance patches are clearly different from those of faunal populations.

In 1994, Baker again analyzed the landscape structure of the BWCA area. In this study, he looked at the restoration of landscape structure following alteration by settlement and fire suppression. The question posed was the analysis of the altered landscape structure produced by fire suppression. Baker again used the modified version DISPATCH model to answer this question. The model consisted of the four parts mentioned above. One shortcoming of the simulation was that it could not model the initiation and spread of fire, so the historical sequence of fire sizes and intervals, as well as the effect of stand age on the probability of ignition, was used.

This study differed slightly in results from the previous study. This is due to a more precise implementation of the shape index and fractal dimension algorithms in the r.le programs. Results suggested that the landscape does not respond uniformly to alteration of the disturbance regime. Measure related to the number of patches restore more slowly than those related to the attributes of patches. One important result was that restoration could be achieved by simply reinstating the pre-

disturbance (pre-settlement and pre-fire suppression) regime without any other manipulation to the system.

One limitation to this method of analysis noted by Baker was that data to run the model are difficult to obtain. This applies to the difficultly of obtaining data on fires, to be able to write an equation describing landscape disturbability. Another shortcoming is that this model had only a probabilistic initiation and spread function; it did not have the physically based spread function seen in Kessell models. However, the use of r.le programs to describe landscape structure was not limited or flawed by the fire-spread limitations.

In the third study, GIS analyses were used to evaluate how human activities affect the landscape structure of jaguar habitat in Sierra de Tamaulipas, Mexico (Ortega-Huerta and Medley 1999). This study focused on the landscape level, as environmental management in the area was only done on a local, parcel-size scale and did not provide an accurate assessment of impacts of regional habitat change. The purpose of the study was to evaluate how human influence on land cover is related to the distribution of important areas for wildlife conservation.

Landscape analyses of jaguar habitat occurred on two levels. First, the area was surveyed to assess potential habitat for the species. Areas of habitat ranked "high" were then re-sampled and imported into GRASS for analysis using r.le programs. Then, land-ownership was assessed for the "high" potential jaguar habitat and analyzed in GRASS using r.le programs.

The study results showed that management of land parcels in Sierra de Tamaulipas needs to be scaled up from a parcel plan to a regional one. This is one benefit of r.le program analysis, as it can be performed on many different scales simultaneously.

Patch Analyst

Source

Elkie et al. 1999

Developers:	Elkie, P.C., Rempel R.S., Carr, A.P. Sustainable Forest Management Network Centre for Northern Forest Ecosystem Research
Contact:	(*none given*)
Web site:	http://flash.lakeheadu.ca/~rrempel/patch/
Use:	Install as extension of ArcView GIS

Overview

Patch Analyst is an extension to ArcView GIS that facilitates spatial analysis of landscape patches and the modeling of attributes associated with patches. There are two versions of the program. The full version analyzes both polygon and grid data structures, and requires the Spatial Analyst extension in ArcView GIS. The vector edition analyzes only polygon data. It works with ArcView shapefiles and grids, and ArcInfo coverages and grids.

There are numerous metrics analyzed in Patch Analyst, including mean/median patch size, patch size CV, edge density, mean shape index, fractal dimension, interspersion and juxtaposition, Shannon's diversity index and core area index. The program is also able to create a new shape with patch metric attributes attached. Summary statistics are reported at the class or landscape scale. Refer to the definitions in FragStats for the various patch metrics.

Patch Analyst has attribute modeling capabilities that allow the user to translate vegetation age and composition into habitat units (or forest age/seral classes) according to pre-defined rules. The spatial analysis components allow the user to assign values to specific spatial configurations of the vegetation/landscape characteristics. Proximity, interspersion and insularity of habitat patches are all assessed within a user-defined spatial unit. The hexagon cell structure is used to delineate spatial units; cell size may be set as a function of an animal's home rage, or to maintain a viable population, etc., allowing hierarchical analyses.

All analysis and summary statistics are summarized in the spatial statistics output table, which can be exported to other programs for graphing and further statistical analysis. This is necessary for assessing the effects of habitat structure on a TES.

Output

The results of the spatial analysis performed in Patch Analyst are given in a spatial statistics output table. The table can be exported as a dBase, Info, or delimited text file, for use in other programs for advanced statistical and graphical analysis (Figure 3). There is an option to export directly to an Excel file worksheet as well.

Patch Analyst analyzes spatial landscape data using a variety of metrics. Table 10 lists applicable metrics and the file type(s). Table 11 lists sample Patch Analyst output. Refer to the FragStats section (p 5) for a description of each statistic.

Table 10. Summary of output metrics calculated.

Group	Statistic	Abbreviation	Applicable on Shape Theme	Applicable on Grid Theme
Area Metrics	Class area	CA	Y	Y
	Total landscape area	TLA	Y	Y
Patch Density & Size	# of patches	NumP	Y	Y
	Mean patch size	MPS	Y	Y
	Median patch size	MedPS	Y	N
	Patch size coefficient of variance	PSCoV	Y	Y
	Patch size standard deviation	PSSD	Y	Y
Edge Metrics	Total edge	TE	Y	Y
	Edge density	ED	Y	Y
	Mean patch edge	MPE	Y	Y
	Contrasted weighted edge	CWED	Y	Y
Shape Metrics	Mean shape index	MSI	Y	Y
	Area weighted mean shape index	AWMSI	Y	Y
	Mean perimeter-area ratio	MPAR	Y	N
	Mean patch fractal dimension	MPFD	Y	Y
	Area weighted mean patch fractal dimension	AWMPFD	Y	Y
Diversity & Interspersion Metrics	Mean nearest neighbor distance	MNN	Y	Y
	Mean proximity index	MPI	Y	Y
	Interspersion juxtaposition index	IJI	Y	Y
	Shannon's diversity index*	SDI	Y	Y
	Shannon's evenness index*	SEI	Y	Y
Core Area Metrics**	Total core area	TCA	N	Y
	Mean core area	MCA	N	Y
	Core area standard deviation	CASD	N	Y
	Core area density	CAD	N	Y
	Total core area index	TCAI	N	Y

Notes:

All core area metrics are per disjunct cores.

*Applicable only at the landscape level

**Core area metrics are directly applicable for grid themes. For vector themes create a core area theme.

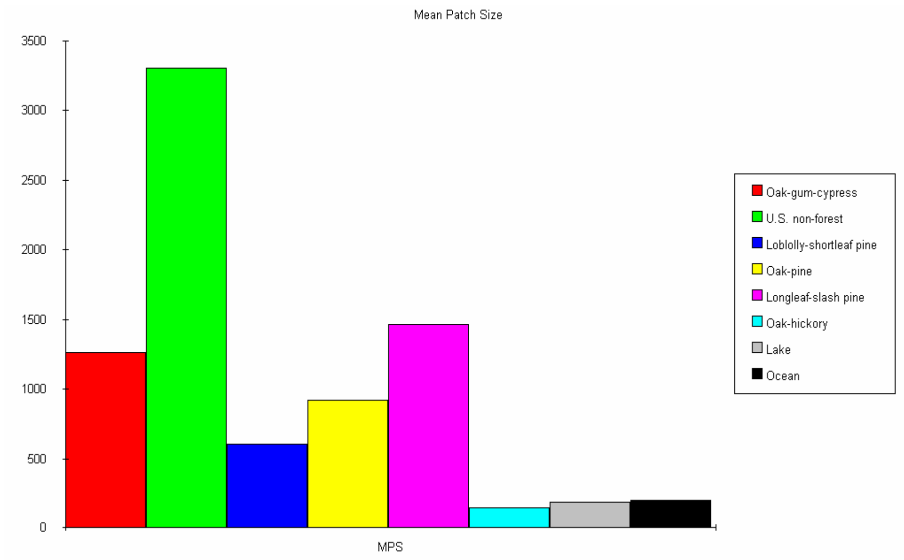


Figure 3. Plot of mean patch size, obtained in ArcView GIS using data from the Patch Analyst program.

Table 11. Example of Patch Analyst output table (showing landscape metrics for a site near Fort Stewart, GA).

Metric	**Value**
CA	9421100
TLA	9421100
NumP	7055
MPS	1335.38
MedPS	100
PSCoV	2494.90
PSSD	33316.36
TE	132010000
ED	14.012
MPE	18712
MSI	1.2996
AWMSI	13.03
MPAR	34.04
MPFD	1.0241
AWMPFD	1.1901
SDI	1.6649
SEI	0.8006

Input

Patch Analyst consists of several scripts written in Avenue and C code, which collectively make up the extension. There are two versions available. The first is a vector only version. It works with ArcView shapefiles and grids, and ArcInfo coverages and grids.

The second version of Patch Analyst is a vector and grid version, which uses the FragStats spatial analyst program (above). A modified version of FragStats is packaged and distributed with Patch Analyst. Use of the second version requires the Spatial Analyst extension in ArcView GIS.

The Patch Analyst extension calculates spatial statistics on both polygon (shape) files and raster (Arc grid) files. Generic image files, such as ERDAS, JPEG, etc. can be imported into ArcView and converted to grid files for analysis as well.

Resources Required

Patch Analyst requires ArcView GIS, version 3.x or higher. For the full version of Patch Analyst, the ArcView extension Spatial Analyst and FragStats are also required. A modified version of FragStats is packaged and distributed with the Patch Analyst extension. Patch Analyst will run on Windows 95, 98, or NT operating systems. For statistical and graphical analysis of data outputs, programs such as SAS, SPSS, and Microsoft Excel are required.

Technical Expertise Required

To use Patch Analyst effectively, one must be familiar with the standard functions and terminology used in ArcView, and the standard terminology and concepts used in landscape GIS analysis (i.e., metrics information).

To calculate ratios and other advanced statistics, one must be familiar with both methods and programs such as SAS or SPSS; to create graphs to display results, one must be familiar with a spreadsheet or database program such as Excel or dBase.

Support

No web site or contact information is listed for the Patch Analyst support. The developer's website (http://flash.lakeheadu.ca/~rrempel/patch/developers.htm) indicates that no ArcGIS (Arc components) version of Patch Analyst are planned. Consequently, Patch Analyst remains an ArcView 3x extension.

Versatility

Patch Analyst is used to assess landscape structure for a variety of habitat types. Patch Analyst is not suitable, however, for analysis of the effects of landscape structure on floral or faunal species. That must be conducted using PCA, regression, or other statistical methods.

Linkage ability

Patch Analyst is an extension of ArcView GIS; therefore all data types that can be imported into that program can be analyzed using Patch Analyst. These include all forms of raster files, grid files and even vector files. Vector files are converted to raster files in ArcView GIS prior to use by Patch Analyst.

The output statistical table can be exported to dBase, Info, or delimited text file for use in other programs for statistical analysis. In addition, Patch Analyst results can be exported directly into Excel for further analysis.

Strengths

One obvious strength of Patch Analyst is the fact that it is integrated into ArcView GIS. This is an advantage over other landscape structure models, which have to be formatted and input into ArcView GIS for further analysis. ArcView GIS provides tools for mapping and graphic analysis of data. Models such as FragStats and r.le programs have to be imported into other programs (i.e., Excel) before graphic analysis can be done.

Shortcomings

The four primary shortcomings of landscape structure models discussed in the FragStats: Shortcomings section (p 12) also apply to Patch Analyst. In addition, Patch Analyst is very time consuming in performing calculations of metrics. This puts limitations on the number of metrics that can be reasonably calculated for a given study (Apan et al. 2002).

Applications

Patch Analyst has been used in studies of habitat mapping and changes in landscape structure. Table 12 demonstrates the uses of Patch Analyst; an outline of three of those studies is provided below.

Table 12. Studies that have used Patch Analyst.

Plant	Invertebrate	Amphibian/Reptile	Fish	Bird	Mammal
Honnay et al. 2003, Apan et al. 2002, Schlaepfer et al. 2002	Backman and Tiainen 2002			Cooper and Walters 2002, Musacchio and Coulson 2001	Hansen et al. 2001

The first study used Patch Analyst in habitat mapping and fragmentation analysis of caribou in British Columbia, Canada (Hansen et al. 2001). The primary objective

of the study was to map caribou habitat for input into Patch Analyst, which would then determine if changes in the level of fragmentation have occurred as a result of increased timber harvesting over a 22-year period from 1975-1997.

The first step in this study was to assess caribou habitat suitability. A Habitat Suitability Index (HSI) model was used, which incorporated elevation, slope, habitat unit, and stand age to determine a total HSI. ArcInfo GRID files were obtained for elevation, slope and stand age used in the HSI calculation. For habitat unit, a Hybrid Decision Tree (HDT) algorithm was used to classify habitat units. HSI's are usually given within a range of 0.0 (poor suitability) to 1.0 (best suitability). However, for the purposes of fragmentation analysis, the HSI's were reclassified into 10 ordinal rank classes ranging from 1 (=0.0 HSI) to 10 (=1.0 HSI).

Next, spatial pattern metrics were quantified and compared between the two time periods (1975 & 1997). The metrics were generated using Patch Analyst, which calculated several landscape metrics at both the landscape and class levels.

Fragmentation analysis was then performed at two levels. At the first level, spatial metrics were calculated for each of the 10 HSI classes. The second level of fragmentation analysis was conducted on binary maps, where suitability was considered to be greater than a specified suitability threshold. In both levels of fragmentation analysis, the focus was on changes in HSI class level indices rather than landscape level indices.

After analysis of class area, patch density, mean patch size, patch size coefficient of variation, mean core area, edge density, and mean proximity index, the authors concluded that both landscape configuration and composition have been altered over the 22-year study period. They concluded that this was a result of timber harvesting and wildfires, which led to an increase in fragmentation of the study area.

Apan et al. (2002) conducted the second study. Their focus was on mapping and analysis of changes in riparian landscape in Queensland, Australia. The purpose of the study was to develop appropriate mapping and assessment techniques to quantify the nature and magnitude of changes in riparian landscape structure within a catchment.

The first step in their analysis was to produce reliable land use/cover maps for two satellite images in the study area, one from 1973 and one from 1997. Next, Patch Analyst was used to quantify landscape structure for each of the two land use maps and to analyze change in landscape over time. This study focused on woody vegetation. A map overlay was performed to create a thematic map depicting all possible

combinations of land use change; changes in woody landscape were further analyzed.

Results of this study show that woody vegetation was cleared mainly for pasture. Results showed that riparian vegetation has undergone considerable fragmentation over the 24-year study period. This information could be valuable in future management of riparian zones.

The goal of the final study was to describe bumblebee assemblages in field margins of one Finish area in relation to habitat availability and quality, and density of food plants (Backman and Tiainen 2002).

Patch Analyst was used to calculate landscape indices for the patches of farmlands. Aerial orthophotographs were verified with fieldwork for use in Patch Analyst.

The results of this study showed that width of field margins had a strong effect on bumblebee density. However, width of field margins did not correlate with species richness or diversity. The most important factor in bumblebee distributions appeared to be availability of a certain plant species, *Trifolium medium*.

Habitat Analysis and Modeling System (HAMS)

Source

Developers: John Roseberry and Quingwang Hao
Contact: jrose@siu.edu
Web site: none

Overview

The Habitat Analysis and Modeling System, HAMS, is a PC-based software program that combines graphical, analytical and modeling capabilities. The program allows users to graphically display, measure, modify and analyze landscape structure. In addition, the program is able to evaluate habitat suitability for a species or group of species, by providing an estimate of the density of the species within the study area. This is done using Pattern Recognition (PATREC) models, specified for the life requirements of the species under study.

Although the program can estimate habitat suitability for a given study area, it cannot predict abundance or species' response to habitat change. As with the first three models evaluated, further analysis such as PCA, regression, or Spatial Analyst modeling must be done for TES assessment.

Output

HAMS operates in two modes, modeling and edit. In the modeling mode, all modifications to an image are temporary; the original image remains unchanged at the end of the session. In edit mode, all changes to the original image may be saved permanently. HAMS calculates landscape metrics for patch classes and landscapes (Figure 4). Table 13 lists the metrics calculated by HAMS. Expanded definitions for these metrics can be found in the HAMS manual.

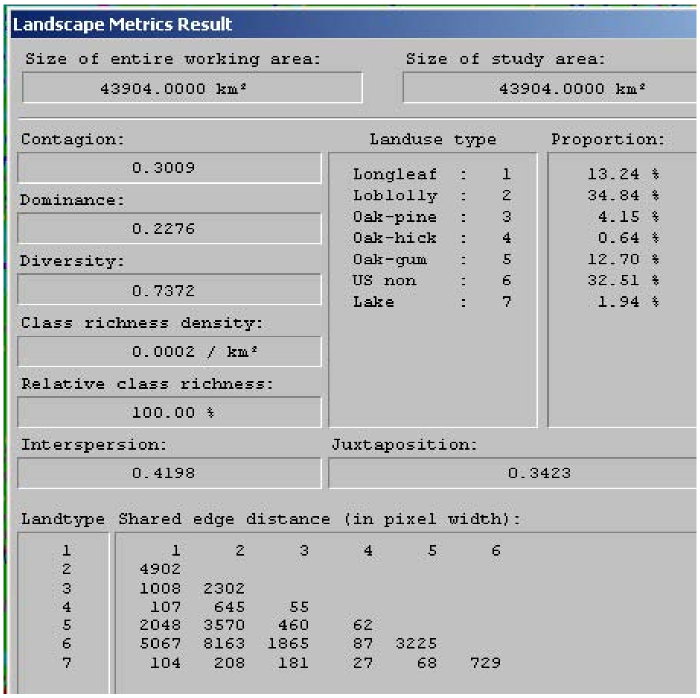


Figure 4. HAMS landscape metrics output for the Fort Bragg area study site. Metrics are used in the PATREC model to obtain an estimated density for the species in the specified study area. In this case, the density obtained was 3.10 RCW/km^2.

Table 13. Summary of output metrics calculated by HAMS.

Class Patch Metrics	Landscape Metrics	Landscape Patch Metrics
Number of patches	Proportions	Number of patches
Mean patch size	Contagion	Mean patch size
Total perimeter	Dominance	Total perimeter
Mean distance to nearest neighbor	Diversity	Mean distance to nearest neighbor
Mean neighbor distance in proximity zone	Class richness	Mean neighbor distance in proximity zone
Mean proximity index	Relative class richness	Mean proximity index
Mean relative proximity index	Shared edge distance	Mean fractal dimension
Mean fractal dimension	Interspersion	Mean modified fractal dimension
Mean modified fractal dimension	Juxtaposition	

Once landscape metrics are calculated, HAMS uses Pattern Recognition (PATREC) models to evaluate habitat suitability of both original and modified landscapes, in the form of a density estimate for the species under study (Figure 5). The results of HAMS can be saved as ASCII files, for use in virtually any other program.

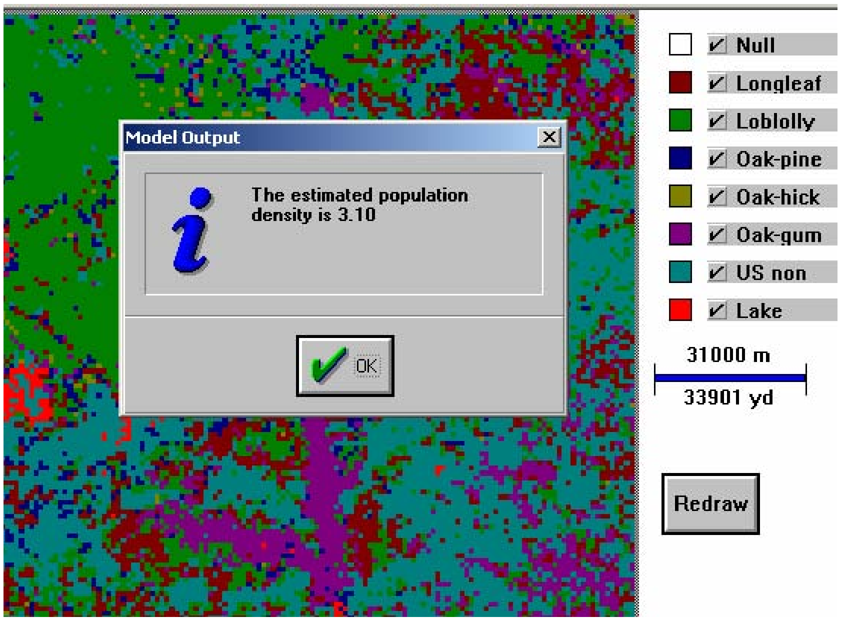


Figure 5. Example of a habitat suitability output, in the form of an estimated species density.

Input

A HAMS (version 1.0) image file has 2 parts, a header and an image body. The image body must have the following characteristics: (1) ASCII format, (2) raster file structure, (3) ≤ 12 class types, (4) class types represented by single alphanumeric characters, and (5) characters separated by 1 or more spaces. Table 14 lists the file format used in HAMS.

Table 14. Input image file format.

Line(s)	Format
1st Line	"HAMS 1.0 Image File"
2nd Line	4 integers separated by a space, representing: # rows, # columns, # classes (n), pixel width in meters
Next n+1 lines	Null class character followed by null class name First class character followed by class name Second class character followed by class name … … nth class character followed by class name

Pattern recognition (PATREC) models are used in HAMS to evaluate habitat suitability. PATREC models use Bayes' theorem of conditional probability to evaluate

habitat suitability based on probabilities that a particular habitat condition is consistent with a set of observed landscape conditions (Roseberry and Hao 1995).

PATREC files can be previously saved models created on-screen, or models created in a text editor and saved in ASCII format. Table 15 list the format attributes required to import PATREC models.

Table 15. Input PATREC file format.

Line(s)	Format
1st Line	"HAMS 1.0 Model File"
2nd Line	4 real numbers: high population density standard, low population density standard, high prior probability, low prior probability
3rd Line	1 integer number: # metrics used in model
Each metric occupies a section of the file	1st Line: metric name 2nd Line: 3 integer numbers, # categories (nc), category type (0=integer, 1=real, 2=category), a flag indicating whether metric is user defined (0=no, 1=yes) Each nc line contains 3 fields: upper category boundary/name, high conditional probability, low conditional probability

To create a PATREC model on-screen, one first must estimate high and low population density standards, and with prior probabilities for each. Next, select the metric variable(s) that you wish to include in the model. Set the ranges to be analyzed, along with high and low conditional probabilities for each. In other words, set the upper boundary for three range classes on a metric, say mean patch size. For each range class, set the probability that, given a high (suitable) patch, the probability that the mean patch size is within that range. When the model is run, the output is a value for the density of the study species within the study area chosen.

Resources Required

HAMS was written Borland® C++ programming language and requires the following hardware and software for operation:

- Processor: i386 required, P5 or above recommended
- Memory: 28MB required, 216 recommended
- Disk Space: 5MB (installation), additional space required for image files
- DOS: MS-DOS® Version 5.0 or later
- Windows: MS-Windows™ Version 3.1 or later.

Technical Expertise Required

To use HAMS, one should have knowledge of landscape ecology, familiarity with techniques to quantify landscape composition and spatial structure, and knowledge

of PATREC habitat models. The program is intended for use as a management tool, but has potential uses in research and classroom applications.

Support

There is no support for HAMS offered in the manual or online. There is a help menu within the program.

Versatility

HAMS is able to model a variety of habitat types, provided there is sufficient image information. HAMS is able to evaluate habitat suitability, via a species' density estimate, using PATREC models, but is not able to analyze or predict the effects changes in landscape structure have on a species.

Linkage ability

HAMS is able to use raster file types that are formatted to specifications listed above. The model is able to output ASCII files, which can be used in virtually any other program for further analysis.

Strengths

The strength of HAMS is its ability to analyze habitat patches and assess habitat suitability via a species' density estimate, all in one program.

Shortcomings

HAMS is little known, hard to obtain, and has no technical support available. Although the program can analyze the suitability of a habitat by providing an estimate species' density, it only uses landscape metric information as specified by the user, who must have expertise in the life requirements of the species, as they relate to landscape structure. Finally, like the other habitat models, HAMS evaluates landscapes based only on habitat, and cannot assess a species' abundance or persistence (viability) in the landscape. The primary method used in HAMS is PATREC, which is not very widely used or recognized.

Applications

A literature search in the BioOne, ScienceDirect, and JSTOR journal collections, and on Web of Science, encountered no studies that used the HAMS program. (The program was referenced as a landscape tool).

Habitat Suitability Index (HSI) Model

Source

Habitat suitability index (HSI) models have no specific source, instruction manual, or web site. There are guidelines to follow when using these models, which can be found in studies that use HSI models (Lancia et al. 1982).

Overview

HSI models are widely used, as they allow wildlife to be represented with other natural resource information by recording or predicting the response of a species to its environment (Kliskey et al. 1999). Habitat is usually a key factor determining a species presence or abundance, but there are also other factors involved, such as food availability. HSI models attempt to quantify habitat quality using factors shown to be important to the species in question. An HSI provides an index of habitat suitability determined by aggregating one or more factors considered life-requisite components; its values range from 0.0-1.0 (Lancia et al. 1982). It should be noted that habitat suitability indicates the habitat quality for the species, not its abundance. HSI models are based on the assumptions that a species will select and use areas that are best able to satisfy its life requirements, and that consequently, greater use will occur in higher quality habitat (Schamberger and O'Neil 1986).

HSI models can be represented in table form, graphically, or in GIS-based maps. They can be used for current habitat mapping or scenario testing to predict outcomes of habitat change.

Output

HSI models can be represented in a number of ways. The "model output" is an index of 0.0-1.0. However, this index can be used and/or manipulated to represent habitat suitability in a table, graphically or through GIS-based maps (Figure 6).

Input

HSI models require information on the life requirements of the species under study. These factors are given a range of suitability values, and then combined in an equation to calculate the overall HSI value. An example would be the following equation (Hansen et al. 2001):

$$\mathbf{HSI_{total} = (HSI_{elevation} \times HSI_{slope} \times HSI_{habitat\ unit} \times HSI_{stand\ age})^{1/4}}$$

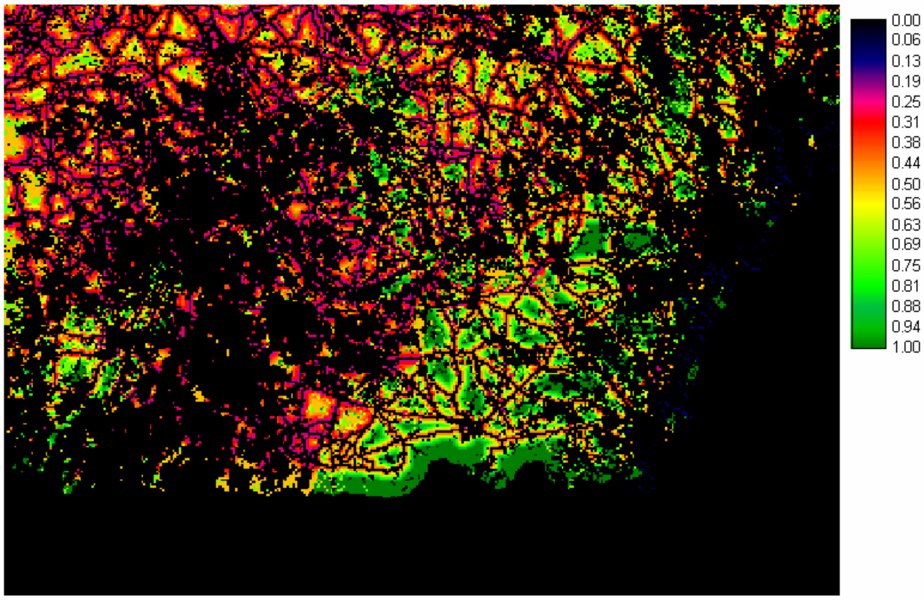


Figure 6. Idrisi GIS map of habitat suitability for the Red-cockaded woodpecker near Fort Stewart, GA. Please note that this HSI was developed for test purposes only, and does not reflect"true" habitat suitability for this species.

As the model is just a calculation of an index, there are no restrictions on data format. The data can be incorporated into a GIS for representation provided it is in a table or database format.

Resources Required

There are no specific computer resources required for the HSI model. This model could actually be used without access to a computer.

Technical Expertise Required

Using the HSI model requires expert knowledge of the ecology and behavior of the species being modeled. In addition, the best representation of the model output is in a GIS, which the user would have to be familiar with.

Support

There is no general support for the HSI model. Support for the specific applications of the HSI model can be obtained through communication with the scientist who has used the model.

Versatility

This model is extremely versatile, as it can be computed for any location and any species, provided there is adequate information on the life requirements of the species in question.

Linkage Ability

The HSI model can accept input from any other model that provides quantitative values. It may be used in conjunction with Patch Analyst (Hansen et al. 2001) or any other program for evaluating landscape structure, to provide a comprehensive assessment of the habitat available to a species. Typically, HSI models are represented in GIS-based maps.

Strengths

One advantage to the HSI model is that it is very simple and straightforward. A computer is not even necessary to compute the suitability of a habitat patch, although one is required to represent suitability and variation in suitability over a large landscape area effectively.

Another advantage of HSI models is that they use life requisite variables other than landscape metrics, such as food availability and climate. A species' suitability to a habitat is rarely, if ever, only a function of landscape structure, and these other variables are extremely important in calculation of a viable HSI.

Shortcomings

One shortcoming of the HSI model is that the variables selected for inclusion in the model, and the shape of the function for each variable, are usually based on expert opinion and can therefore be subjective. In other words, the model is not very robust; different experts, using the same data on the same species, may come up with different models. In fact this is a critical issue with most computer based modeling methods. Those methods can be very sophisticated but if the experts cannot agree upon or clearly describe the critical concerns and limiting factors for a TES, then sophisticated methods cannot really help. It is problem with any of these methods that the biological experts often seem unwilling to make estimates or educated guesses as to what the parameters are for their species. But to use these models requires the best professional estimates. Another important limitation is that the form of the function is restrictive and arbitrary. It does not readily allow for interactions between variables, and often requires assumptions of linearity between a habitat variable and the species' response to the variable (Van Horne 1983).

Finally, a major shortcoming of HSI models as well as other, more advanced habitat modeling methods, is that they describe habitat suitability, but they do not predict the viability or persistence of the species in that habitat, because viability depends on factors other than habitat suitability, including landscape-level factors (total amount of habitat, expected future change in the amount and spatial distribution of habitat, etc.) and demographic factors (survival, fecundity, and dispersal as functions of habitat; exploitation and other impacts not related to habitat, etc.).

Applications

Habitat suitability models have been used in several studies. Table 16 lists some studies done using HIS models. Below is a brief synopsis of three recent studies that used HSI models. Hansen et al. (2001) discusses the Patch Analyst evaluation, as they used HSI models for their study. Hansen et al. (2001) gives an excellent demonstration of the use of HSI models (wildlife) in combination with Patch Analyst landscape structure models (habitat).

Kliskey et al. (1999) evaluated the simulation and alternative resource-use strategies using GIS-based HSI models, for use in natural resource and wildlife management (Kliskey et al. 1999). GIS databases allow for the use of habitat information for development of spatial HSI models. In this case, GIS was also used to test various spatially explicit HSI scenarios for management of woodland caribou, pine marten and timber harvest in the North Columbia Mountains of British Columbia. The model variables (i.e., species' habitat needs) were related to the capability of the habitat to support the species in question. These could be practically measured for application to the model. Then the relative importance of each in meeting life requirements was combined (weighted) in a single equation, one each for the pine marten and woodland caribou. These suitabilities were then used in scenario testing with varying levels of timber harvest, to predict its effects on both species' populations. This study demonstrated that simulation modeling using habitat suitability indices makes it possible to project habitat change and develop provisions for the maintenance or improvement of conditions for wildlife species in question.

Table 16. Studies that have used the HSI model.

Plant	Invertebrate	Amphibian/ Reptile	Fish	Bird	Mammal
	Cake 1983		Jessup 1998, Engel et al. 1999	Tamis and Van't Zelfde 1998, Kliskey et al. 1999 Huettmann and Diamond 2001	Reading et al. 1996 Kliskey et al. 1999 Kiurttila et al. 2002

Tamis and Van't Zelfde (1998) used data from the Netherlands national database to develop a habitat suitability model for several species of birds. The goal was to take data collected on a coarse spatial scale and break it down to a finer scale (disaggregate) for habitat suitability mapping and estimate the potential success of breeding pairs for several species of birds. The authors used the Landscape Ecological Mapping (LKN) database of the Netherlands to find data on abiotic and biotic landscape features they use to generate habitat suitability results for 14 ecologically distinct species of birds.

The analysis process first defines an ecological profile, the species' habitat requirements and sensitivity to anthropogenic disturbance, for each species. Salinity, vegetation structure, moisture conditions, nutrient availability, parent material, and rate of flow were categorized as habitat requirements. Disturbances included roads, urban areas, high-tension grids, and sight blocking vegetation. Habitat characteristics of each 1km grid cell are derived for each of the habitat factors above. The bird data was used to calculate an overall habitat suitability assessment. The last step in this procedure was to convert the corrected suitability into a number of breeding pairs per 100ha, using minimum area information. The results of this study demonstrate the ability to interpolate faunal data based on habitat suitability assessment.

Jessup (1998) used HSI models in simulations of brown trout population dynamics and habitat quality in Maryland. Jessup states that efforts must be made to maximize the carrying capacity of the landscape for both humans and natural needs.

Habitat suitability indices were previously calculated for brown trout. In this case study on the dilemma for brown trout in Maryland, 18 parameters from the HSI were measured in six watershed sites. The critical parameter data collected was then indexed according to the standard HSI 0.0-1.0 scale. Each parameter index was compared within a subset of parameters pertinent to each of the life stages of brown trout. The lowest index value of the life stage subset was then considered the HSI value for that life stage, representing the limiting habitat factor.

The results of the model simulations and a sensitivity analysis performed showed that juvenile HSI values produced the greatest range in population size, which indicates that juvenile habitat has the greatest influence in limiting or influencing the adult population size. These are preliminary indicators for the possible outcomes of various construction activities proposed for the enhancement of human and economic growth.

California Urban and Biodiversity Analysis Model (Curba)

Source

Landis et al. 1998
Developers: John Landis, Michael Reilly, Pablo Monzon, & Chris Cogan
Contact: Phone (510) 642-5918
E-mail: jlandis@uclink.berkeley.edu
Web Site: http://www.cs.berkeley.edu/~kwei/projects/curba/ (July 2005)
Use: Install

Overview

The CURBA model was developed as an ArcView GIS* tool to help urban planners evaluate the effects of alternative patterns of urban growth, and on policies on biodiversity and natural habitat quality. CURBA helps to direct urban growth while promoting environmental and ecological quality. CURBA brings together a statistical model of urban growth with spatial and non–spatial components, procedures for simulating urban growth and effects of various growth policies, and detailed map layers depicting habitat and urban factors.

CURBA consists of two major components, the Urban Growth Model and the Policy Simulation and Evaluation Model. The Urban Growth Model assists in calibration of equations that describe past urbanization patterns, and the application of equations to project future development patterns. This model consists of at least one logit equation that compares observed land changes to spatial and non-spatial factors. Once the logit model(s) have been estimated and checked for accuracy, the coefficients are used to calculate probabilities for future urban growth.

The Policy Simulation and Evaluation Model projects how alternative development policies will affect future urbanization patterns and the associated impacts on habitat integrity. It involves four steps:

1. Import and display urbanization grid calculated by the Urban Growth Model.
2. Enter the population growth increment in persons per hectare, to those grid cells that are suitable for development.
3. Allocate population growth to developable sites by the CURBA model.
4. Compare the resulting growth patterns with habitat designations.

* It has now been upgraded to run with ESRI ArcGIS in Visual Basic. The ArcGIS Version 8 or greater is currently (as of July 2005) available beginning at the web site: http://www.cs.berkeley.edu/~kwei/projects/curba/

Once alternative urban growth scenarios have been generated by the model, it can then analyze landscape structure effects, particularly habitat fragmentation. Class metrics calculated by CURBA include total habitat area, percent of landscape, No. of patches, minimum and maximum patch size, mean patch size, patch size variance and standard deviation, patch density, largest patch index, total edge, average edge-area ratio, and edge density. These metrics can be calculated for all class types or only those specified.

CURBA is used in conjunction with ArcView GIS and various Avenue scripts. The model addresses questions on the effects of community actions and characteristics on land use patterns. It provides maps and tabular summaries predicting impacts of projected urban growth scenarios on the natural habitat.

Output

CURBA is able to use the following categories in simulations: urban (does not distinguish between commercial, industrial or other types), agricultural, forest, wetlands, water, preservation, and parkland. CURBA provides maps and tabular summary outputs of the evaluation results predicting impacts of projected urban growth on various habitat types. In addition, the evaluation can be shown as an ESRI shape-file (polygon) or grid file. Shape-files can be converted to bit-mapped images and graphical displays of the model results.

Input

There are a variety of input requirements that depend on the goals of the model user. They include, but are not limited to, the following database and/or raster data:

- information on land use types (which can be databases or images in raster format)
- vegetation types (from GAP data sets)
- digital elevation model for slope and elevation data
- locations of road, hydrographic line features, major water bodies, etc. (can be obtained through Census Bureau TIGER files)
- jurisdictional boundaries (Census Bureau TIGER files)
- wetlands and flood zones (FEMA)
- other socio-economic data

Resources Required

CURBA requires a 300MHz or higher PC with 32MB of RAM, 300MB of hard disk space, Windows® operating system, SAS or SPSS statistical analysis software, and ESRI ArcView GIS.

Technical Expertise Required

To effectively use the CURBA model, one must be familiar with SAS or SPSS statistical analysis software and ESRI ArcView GIS.

Support

Support for the CURBA model is available through the developer, at e-mail: jlandis@uclink.berkeley.edu.

Versatility

CURBA is designed specifically to examine changes in the urban environment and the effects those changes have on the natural habitat and wildlife.

Linkage ability

The CURBA model could accept data from a variety of models and software programs, provided they are formatted to operate in the ArcView GIS program. The output of the CURBA model can be exported to a variety of programs as well, as it is given in tabular as well as graphic format.

Strengths

According to a guide for CURBA, it is accessible and easy to use. However, a search of various web sites, including the UC Berkeley and ESRI sites, found no further information on the use of CURBA. Links listed in abstracts and overviews of the model do not connect.

CURBA is stated to be fast and flexible. It reveals trends and patterns, allowing one to better understand the driving mechanisms behind urbanization. Finally, CURBA allows users to project future urban growth pattern, the sensitivity of urban growth to alternative regulatory and environmental policies, and the effects of projected growth on habitat integrity and quality.

Shortcomings

One shortcoming to CURBA its emphasis is run simulations in an urban setting only. It does not focus on questions related to the natural environment. In addition, errors are likely from misclassification of data, from misalignment of map feature boundaries, and from limitations in explaining historical urban growth patterns based on statistical methods (Agarwal et al. 2002).

CURBA projects the future based on the past using regression methods, which means that the results rely on how well the Urban Growth Model explains historical growth patterns and the extent to which these patterns drive or resemble future development. For natural landscapes, historical patterns of change are not as readily available, and, even if they are available, simple regressions can be used to extrapolate such patterns to the future only to a very limited extent (for example only for a few years).

Applications

CURBA has not been used for TES assessment, and the supporting documentation does not provide methods for, or examples of, such analyses. A search of BioOne, JSTOR, and ScienceDirect yielded no empirical or theoretical studies that used the CURBA model. However, an electronic paper was found on GISCafe.com, and another in the ESRI web library, both of which are summarized below.

The GISCafe.com article summarized alternative futures for the Mojave Desert based on several model scenarios (Stevenson et al. 2003). The project was undertaken to study urbanization in cities adjacent to the Mojave Desert. Increased urbanization could drive species onto military bases in the area, which could hamper the mission efforts of personnel on those bases.

To model alternative futures in the Mojave, three primary drivers of landscape change were assessed: socio-demographic, economic, and biophysical. Each driver used a different model, a unique set of data, and required assumptions specific to it.

The socio-demographic model used county-based population projections to determine the share of total county population found within the Mojave. The county population was then projected into the future, and, using the share seen in the Mojave, increases in population were projected specific to the desert over the next 20 years.

The economic driver centered on factors influencing the location of urban growth, and used the CURBA model for analysis. The CURBA model used four parameters

when projecting urban growth in the Mojave: (1) determination of where urban growth has happened in the past, (2) identification of other explanatory variables for growth, (3) use of the explanatory variables in a logit model to create a probability surface that ranks the likelihood of development on a scale from 0 to 1, and (4) ”population” of the probability surface using the Mojave population projections.

For the biophysical driver, the authors adopted a hierarchical approach to relationships, using vertebrates in multi-species, focal species and single species segments. Distribution models for each level were obtained from the California Wildlife Habitat Relationships Program (California Dept. of Fish and Game). The models included the general expanse of land and range of elevations where each species was predicted to occur, and were developed from the relationship of each species to particular habitat types.

Seven scenarios were simulated in the model. Following simulations, the loss of habitat and identification of species that may be driven on military installations were determined. This information may be used when plans for future development in the Mojave Desert are considered.

This paper served to illustrate the use of the CURBA model, which was used in conjunction with other models to assess the impact of various plans of urbanization. Please note that the CURBA model was used only to determine the economic drivers for urbanization, not to analyze the biological effects of urbanization.

The article found in the ESRI web library was the source document for the CURBA model Landis et al. 1998. The majority of this article presents the CURBA model in detail, and then applies it to a pilot study in Santa Cruz. For this pilot study, the CURBA model was used to test the effects of three different development scenarios in the Santa Cruz area. The scenarios were “no constraints,” “farmland protection,” and “environmental protection.” In the “no constraints” plan, development could occur anywhere but on wetlands. “Farmland protection” also provided protection for prime and unique farmland, and farmland considered valuable to the economy. Finally, the “environmental protection” plan prohibited development on wetlands, floodzones, sites with slopes >10%, and within 100m of a river. Development also had to occur within 500m of sphere-of-influence boundaries.

After running the model with each scenario, maps were generated showing predicted areas of development and non-development. An analysis of habitat fragmentation on two habitats, agriculture and upland redwood forest, showed interesting results. The “farmland protection” scenario actually resulted in more fragmentation for agricultural areas, while the “environmental protection” scenario resulted in more fragmentation for the upland redwood forests. This leads to the conclusion

that, while policies designed to protect the environment are favorable, they do not always protect the habitat designed for. One should first test all scenarios prior to making a decision on policy.

Land Transformation Model (LTM)

Source

Pijanowski et al. 2002a

Developer:	Dr. Bryan C. Pijanowski
Contact:	Phone (517) 432-0039
	pijanows@msu.edu
Web site:	http://www.ltm.msu.edu
Use:	Install; must also have ArcView GIS and SNNS software

Overview

The Landscape Transformation Model (LTM) uses landscape ecology principles and patterns of interaction to simulate land use change processes, and to forecast land use change. The model can be used in any landscape, but was designed for use in watersheds. The conceptual LTM contains six interacting modules:

- *Policy framework*, which organizes goals for stakeholders. Goals may include the control of pollutant inputs, ecological restoration, or habitat preservation.
- *Driving variables*, which contain three categories: (1) Management Authority, important because lands owned by Federal or state governments must be excluded from development, (2) Socioeconomic variables including population change, land ownership economics, transportation, agricultural economics and locations of employment, and (3) Environmental variable of land transformation (abiotic or biotic).
- *Land transformation*, which is the change in land use and land cover. Land use types include urban, agricultural/pasture, forest, wetlands, open water, barren and non-forested vegetation. Land cover types include types of agriculture (row/non-row crops), deciduous and coniferous forest, and non-forested vegetation.
- *Intensity of use*, which considers land management practices, resource use and human activities.
- *Process and Distribution*, which characterizes groundwater and surface water flows, chemical and sediment transport across land through rivers and streams, and geochemical interactions and fluxes.
- *Assessment endpoints*, which provide indicators of ecological integrity and economic sustainability. This module is used to quantify the nature of landscape changes.

Although the conceptual LTM has six modules, not all have been used in practice. Using the LTM model requires four sequential steps:

1. Processing of spatial data.
2. *Applying Spatial Transition Rules*. The LTM uses four classes of transition rules: neighborhoods or densities, patch size, site specific characteristics, and distance from location of a predictor cell. Locations are coded with a "0" if they are excluded from development; these locations are then multiplied together to generate one layer of "exclusionary zones."
3. *Integration of Predictor Variables*. There are three different integration methods that can be used with the LTM, each of which requires a different type of data normalization. They are multi-criteria evaluation, artificial neural networks, and logistic regression. The output of this step is a map of change likelihood values, which specify the relative likelihood of change for each cell based on the integration result.
4. *Temporal Indexing*. This step determines the amount of land expected to transition to urban over a given time period, using a "principal index driver" (PID). PID is calculated based on population growth and historical population density, to determine the total amount of new urban land at a later time.

Calibration and use of the LTM model requires expertise in land-use modeling and the C language of programming, as well as Stuttgart's Neural Network Simulator (SNNS) neural network batch files. However, the model outputs are easy to understand GIS maps and Excel files.

The LTM is not capable of assessing a TES within a static or changing habitat. As stated with respect to previous models, further statistical analysis must be done to analyze TES within a given habitat.

Output

The LTM addresses up to eight different land use types, including residential, urban, agricultural, forest, wetlands, water, parkland, and non-forest vegetation. The model can then address the effects of land-use patterns from changes in transportation infrastructure and city/county master plans. The model is also capable of addressing the effects of changing land-use patterns on environmental quality.

Outputs of the LTM include a time series of projected land uses in the project area at specified time steps. Land use projection maps are given in ArcView or ArcInfo GRID files. Data summaries of the model output are given in Excel files.

Input

To operate the LTM, the user must have a GIS database that contains basic land use information. Table 17 lists the data format and minimum data required.

Table 17. Input data types and format.

Input	Format
Previous land use	ArcView or ArcInfo GRID
Roads, highways, streets	ArcView or ArcInfo Lines
Surface water	ArcView or ArcInfo lines or polygons
Elevation	ArcView or ArcInfo GRID
Public lands	ArcView or ArcInfo GRID
Population	ArcView or ArcInfo GRID
Per capita use requirements	ArcView or ArcInfo GRID

When using the neural network (step 3), a C program was written to convert the data into pattern files (ASCII format), so that the SNNS neural network can understand the data.

Resources Required

Use of the LTM requires a 300 MHz or higher PC or Sun Sparc with a minimum of 256 MB of RAM, a Windows NT or Sun Solaris operating system. Software requirements are spreadsheet (Excel), database (MS Access), statistical (S-Plus, SAS), programming language compiler (C), GIS (ArcView or ArcInfo) and Stuttgart Neural Network Simulator (SNNS).

Technical Expertise Required

Users of the LTM model must have expertise in land-use modeling, GIS, statistical analysis, the C language of programming, and in artificial neural networks (in particular, in preparing SNNS neural network batch files).

Support

Support for the LTM model is available through URL:
http://www.ltm.msu.edu

Contact the program developer at e-mail:
pijanows@msu.edu

Versatility

The LTM model is used to model urbanization and other land-use transformations. It is not used to model the effects on a particular species. The model can be used in any landscape, although it was designed for use in watersheds.

Linkage Ability

Inputs to the LTM model are very specific ArcView or ArcInfo GIS GRID, line and polygon files. The model outputs files in ArcView GRID format, and data summaries are given in Excel format. Data summaries can be converted to any database format for use in other programs.

Strengths

The GIS outputs of LTM provide stakeholders and resource managers with results that are easy to view and understand.

Shortcomings

According to EPA (2000), there are several limitations to use of the LTM. First, the "drivers" are not dynamic. It is estimated that projective ability is only about 35 percent for a 100m x 100m cell size. Second, it takes several large C programs to couple the GIS and neural network simulation software. Third, the model requires large amounts of memory (2 GB of RAM for a 5-7 county area). Finally, the model requires extensive training and experience to run.

LTM, like CURBA, is based on projecting historical patterns of land-use change. Thus, it has the same limitation as CURBA: the utility of using historical patterns for predicting future change in natural landscapes is limited, are likely to be inaccurate or accurate only for very short time horizons.

Applications

The Land Transformation Model is fairly new Pijanowski et al. 2002a. A literature search found two studies that used the model, both performed by the developer.

The first article by Pijanowski details the LTM model and presents its use in Michigan's Grand Traverse Bay Watershed (GTBW) (Pijanowski et al. 2002a). The first half of the paper outlines the LTM model and use of ANN's (artificial neural networks) and GIS. The second half of the paper goes on with an empirical study in the GTBW, summarized here.

The purpose of the study was to develop a control run of the model within GTBW and to illustrate the extension of the county level model for predicting development patterns within the six-county GTBW site. The LTM was applied in two groups of runs, the control run and the predictive run. The control run used LTM to project patterns of urban development using an ANN trained on actual changes between 1980 and 1990. The predictive run extends the same ANN to project 1990 urban land development.

Ten predictor variables and exclusion zones were compiled into ArcInfo GIS. They are density of agriculture, distance from highways, distance from lakes, distance from lakeshore, distance from rivers, distance from roads, distance from residential streets, distance to urban use, distance to recreation sites, and quality of view.

The ANN was tested with various input data to develop a network with satisfactory predictive capability. ANNs were applied to the prediction of land-use change in four phases: (1) design of network and of inputs from historical data, (2) network training using a subset of inputs, (3) testing of the neural network using the full set of data inputs, and (4) using the information from the neural network to forecast changes.

For the ANN test, the network files generated from a training exercise were applied to a pattern file that contained all of the cells in the county tested. SNNS (Stuttgart's Neural Network Simulator) then used the pattern file and network file to generate an output file of activation values, called a result file. The result file had values ranging from 0 (no chance of urban development) to 1 (highest chance urban development).

Next, GIS was used to determine if the transitions predicted by SNNS were accurate to what occurred from 1980-1990. The model was then evaluated regarding its ability to predict locations of urban development accurately and regarding which predictor variables were most influential in the model's ability to predict urban changes. The model was tested for one county with data and then scaled up to all six counties in the GTBW site.

LTM results showed an accuracy of 46 percent of the time at a 100m x 100m cell size. Scaled up to 1km x 1km, the accuracy of the LTM increased to 65 percent. The model was able to predict a change likelihood of 0 (no change) in 56,762 cells of 63,744 tested; 208 cells had likelihood values of 1 (highest likelihood of urban change).

The results of the test to see which predictor value had the most influence on urbanization varied with spatial scale. At the scale of < 1km x 1km, quality of view

had the most influence; county road distance was the most influential at a scale > 1km x 1km.

When the ANN pattern file was generated for the entire watershed, the forecasts of urban growth appeared reasonable and were concentrated in tourist towns near inland lakes or along the lakeshore. This adds confidence to the LTM in predicting future urbanization.

Pijanowski et al. performed another study to assess the impact or urban sprawl in coastal watersheds of Lake Michigan (Pijanowski et al. 2002b). Once again, the LTM model was used, this time to predict land use change in coastal watersheds of Lake Michigan, to apply several ecological assessment metrics to past, current and future land-use changes, and to discuss the implications of the model results in the context of the Lake Michigan Lakewide Management Plan (EPA 2000).

First, an analysis of the relationship between urban growth and population change was conducted to parameterize the model. When conducted statewide, the relationship had an index range of 2.3 (Ann Arbor metropolitan area) to 8.7 (study area). Next, the driving variables were identified. They were distance to transportation, proximity to amenities, exclusionary zone and population forecasts. These variables were written to ASCII grid files for use in the ANN.

An ecological assessment of urbanization was then conducted, in which several landscape metrics were examined. They included percent urban in watershed, human-use index, amount of forest along streams, nitrogen loading from uses, loss of prime farmland, and distance of urban from the Great Lakes' shoreline.

The results of this study showed that the greatest amount of new urban use will be along the coastal watersheds, some watersheds will become hydrologically impaired from this increased urbanization, some riparian habitats may be lost along major rivers draining into Lake Michigan, the amount of natural habitat will be reduced, threatening sustainability of wildlife, and the amount of prime farmland lost will be proportionately greater than the increase in urban land use. The Black-Makatawa watershed is likely to be impacted most from urbanization. The LTM forecasts of this study can be used to anticipate consequences of change, so that policy can be developed to mitigate negative effects of urbanization on watersheds.

Land-Use Change Analysis System (LUCAS)

Source

Berry et al. 1995

Developers:	Michael W. Berry, Richard O. Flamm, Brett C. Hazen, Rhonda M. MacIntyre, and Karen S. Minser.
Contact:	Phone (865) 974-3838
E-mail:	berry@cs.utk.edu
Web site:	http://www.cs.utk.edu/~lucas
Use:	install LUCAS and GRASS

Overview

LUCAS was developed in 1994 as a prototype computer program, to examine the impact of human activities on land use and the subsequent environmental and natural resource impacts. The model stores, displays and analyzes map layers derived from remote sensing images, maps, and outputs from econometric models using the GRASS system. Simulations using LUCAS generate new maps of land cover showing the amount of change over a specified time period. The model can address issues such as biodiversity, species abundance, landscape integrity, changes in real estate values, and land-ownership characteristics.

LUCAS is a spatially explicit modular system that consists of three modules linked by a common database of driving variables. The three modules are:

- *Socioeconomic models*, used to derive transition probabilities associated with land cover changes. Socioeconomic driving variables include transportation networks, slope, elevation, ownership, land cover, and population density. Use of this module requires an expert in socio-economics.
- *Landscape change model*, which receives as its input the transition matrix produced with the socioeconomic module. One iteration of this model produces a map of land cover reflecting socioeconomic motivations behind human land-use decisionmaking.
- *Impact models*, which use land cover maps produced by the landscape change model above to estimate the impacts to environmental and natural resources. Examples of environmental variables include the amount and spatial arrangement of habitat for a given species and changes in water quality caused by human use.

LUCAS assumes that market processes, human institutions, landowner knowledge and ecological processes influence fragmentation, connectivity, spatial dynamics and the degree of dominance of habitat types. The concept of land cover transition is central to the LUCAS model. Transition probabilities govern changes in land cover, and are derived empirically through a time series analysis of changes in land

cover, while considering road networks, population density, and physical attributes of the landscape.

LUCAS can compare multiple scenarios by running multiple simulations that vary the land cover dependent variable. The graphical and statistical outputs generated by LUCAS can then be compared.

Output

LUCAS was developed to address the effects on land-use patterns from changes in transportation infrastructure, local zoning, and city/county master plans. The model can address the effects of changing land-use patterns on availability of open space and environmental quality.

The output of LUCAS includes a time series of projected land uses at user specified time steps (Figure 7). Table 18 lists sample LUCAS output information.

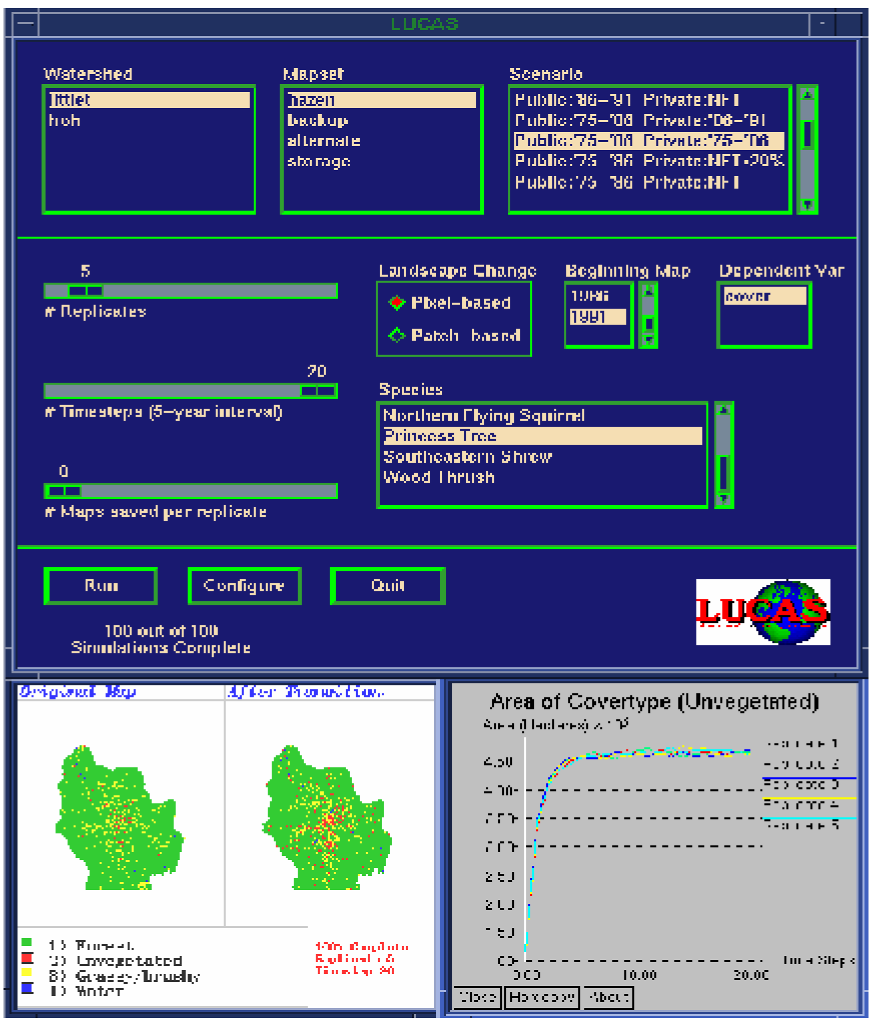


Figure 7. Example of output data from the LUCAS model.

Table 18. Output calculations and file types.

Output	Format
Area	ASCII and graphical
Amount of edge	ASCII and graphical
Edge/area ratio	ASCII and graphical
Mean patch size	ASCII and graphical
Number of patches	ASCII and graphical
Cumulative frequency distribution of patches by size	ASCII and graphical
Proportion of land cover	ASCII and graphical
Amount of total edge	ASCII and graphical
Standard deviation of patch size	ASCII and graphical
Size of largest patch	ASCII and graphical
Mean patch shapes	ASCII and graphical

The GRASS map layers produced in LUCAS can also be stored and re-analyzed in an iterative fashion.

Input

To operate LUCAS, the user must have several types of information in GRASS grid (raster) format. These include transportation networks (access and transportation costs), slope and elevation (indicators of land-use potential), ownership, land cover (vegetation), and population density. Although the GIS used by LUCAS is GRASS, most other GIS software can convert their files to the GRASS format.

To run a simulation, the user would first choose the dependent variable for simulated change. Choices given are land-cover, land use, and ownership boundaries. Currently, only the land-cover variable is in operation. Next, the watershed, maps and start year are chosen. The landscape change scenario is chosen from a list of pre-defined scenarios that generate transition probabilities that reflect land use change. Here, the user can specify change in with a resolution of pixels or patches. The third step involves choosing the numbers of replicates, time steps and saved maps. Finally, users can select species impact module(s), which will evaluate the amount of suitable habitat for a target species for each map. Once all of the above selections have been made, the user may then run the model.

Resources required

LUCAS requires a UNIX-based workstation (e.g., Sun SPARC) and Microsoft Windows with the OSF/Motif library toolkit (version 1.21). GIS (GRASS) and spreadsheet software is also necessary, to analyze results. Calibration and use of the model also requires the “C++” program.

Technical Expertise Required

Use of the LUCAS model requires expertise in landscape management, the C++ programming language, and the GRASS GIS program.

Support

Support for the LUCAS model is available through URL:
http://www.cs.utk.edu/~lucas

Contact the developer at e-mail:
berry@cs.utk.edu.

Versatility

LUCAS can be used with any type of landscape and species for which data are available.

Linkage Ability

LUCAS can accept raster grid files from any GIS program although it uses GRASS GIS. Output maps can be analyzed in any GIS program; output statistics can be analyzed in any spreadsheet or statistical program.

Strengths

LUCAS provides a graphical user interface that is intuitive and easily understood by modelers. LUCAS has been used to analyze impacts of land cover transitions on habitat availability for several species (see "Applications," p 12).

Shortcomings

LUCAS uses the public domain GRASS GIS software. There are several bugs in this program, and some of the features of GRASS are not well documented (EPA 2000). Also, use of the model requires training and experience to calibrate. As with the LTM, it is not an off-the-shelf product, but was developed for use by a researcher working with resource managers.

LUCAS, like CURBA and LTM, is based on projecting historical patterns of land-use change (although it uses transition matrix probabilities instead of regression). Thus, it has the same limitation as CURBA and LTM: the utility of using historical

patterns for predicting future change in natural landscapes is limited, are likely to be inaccurate or accurate only for very short time horizons.

The study that used LUCAS for habitat assessment (see below) had only very broad categories for natural types of land cover (e.g., “deciduous forest”). This level of broad definition may not be suitable for assessing the habitat for the more specialized TES.

The transition matrix method used in LUCAS is a pixel-based and independent-grid method, and as a result, tends to fragment the landscape for some land-uses (Agarwal et al. 2002).

Applications

A literature search using BioOne, JSTOR and ScienceDirect found only one article that used the LUCAS model in an empirical study: Pearson et al. (1999). A summary is provided below.

In 1999, Pearson et al. looked at landscape change and habitat availability in two locations, the Southern Appalachian Highlands (NC) and the Olympic Peninsula (WA). The goal of the study was to estimate ecological effects of land cover change in two watersheds, by projecting changes in abundance and distribution of select species. They addressed two questions: (1) how does land ownership affect the availability of suitable habitat for a variety of species in changing landscapes, and how do restrictions on forest harvest change habitat availability? and (2) are species differentially affected by land cover changes that vary among landowners?

To answer these questions the authors used the LUCAS model to simulate land cover change. Land cover, land ownership class, elevation, slope, aspect, distance to nearest road, distance to nearest market center and human population density were used in the LUCAS model. Landscape change was simulated using conditional transition probabilities (refer to article).

For the species assessment, the authors selected eight representative species from each location, due to complexity in discerning consequences of landscape change for a even a small number of species and the limited data availability on several species. The species chosen all had very diverse habitat requirements, which was adequate to assess the implications of landscape change driven by landownership.

Two sets of simulation experiments were conducted to compare effects of alternative scenarios on suitable habitat for the study species. Each simulation compared four scenarios (Table 19).

Table 19. Summary of the questions asked in Pearson et al. (1999).

Simulation	Scenario
Question 1 (see above)	Observed land cover changes 1975-1986
	Observed land cover changes 1986-1991
	1986-1991 observed rates of land cover change, but with constraint prohibiting loss of forest within 90m of a stream and on slopes > 20%
	1986-1991 observed rates of land cover change, but with constraint prohibiting all forest loss
Question 2 (see above)	1975-1986 on public and private lands
	1975-1986 on public land, 1986-1991 on private land
	1986-1991 on public land, 1975-1986 on private land
	1986-1991 on public and private lands

A factorial simulation design was used, as transition probabilities between land cover changes were not stationary between time periods. In addition, all simulations were replicated 5 times due to stochasticity; they were run for 100 years with a 5-year time step and t_0=1991.

Variation in habitat metrics for each species was analyzed with SAS, to test for significant differences in habitat metrics due to the alternative land cover change scenarios. ANOVA and Tukey's Studentized range tests were used to test differences in each metric among scenarios in Question 1. To determine the impact of land ownership on species habitat, a 2-factor MANOVA was used (public vs. private land ownership). Each ownership factor had two levels of transition disturbance, high (1975-1986) vs. low (1986-1991).

The results of this study revealed several key points for ecosystem management: (1) habitat changes for species were only partially predicted by land cover change, (2) simple changes in land cover pattern can produce complex changes in species habitats, and (3) patterns of land ownership influence policy options for conserving regional biodiversity, by affecting the rates and patterns of land cover change. Furthermore, this study indicates that changes in habitat abundance should be assessed separately from those concerning the spatial pattern of habitat, i.e., fragmentation. The recommendation of the authors is to link land cover change models with habitat models to predict possible outcomes of various land management decisions for species of interest.

RAMAS GIS

Source

Akçakaya 2002
Developer: H. Resit Akcakaya
Contact: Applied Biomathematics, 100 North Country Road, Setauket, NY 11733.
Phone: (631) 751-4350
E-mail: info@ramas.com
Web site: www.ramas.com
Use: Install

Overview

RAMAS GIS is designed to link GIS-generated landscape data to a species' metapopulation model for extinction risk assessment, viability analysis, reserve design and wildlife management. It works by combining landscape spatial data, habitat requirements of a given species, and demographic data into a metapopulation model. The model is then run to simulate future changes in species abundance and distribution in the landscape, or to estimate the risk of extinction or decline and time to extinction. The model can be run for varying landscape structures, to assess a species response to development or management actions. RAMAS GIS consists of five programs: Metapopulation, Spatial Data, Habitat Dynamics, Sensitivity Analysis, and Comparison of Results (Table 20).

Table 20. Overview of five sub-programs in RAMAS GIS.

Program	Purpose
Metapopulation Program	• Used to build stage-structured spatially explicit metapopulation models • To run simulations with these models • To predict risk of species extinction, time to extinction, expected metapopulation abundance and its variation and spatial distribution
Spatial Data Program	• Used to calculate the spatial structure of the metapopulation model, to determine characteristics of populations inhabiting habitat patches (carrying capacity, initial abundance, vital rates, etc.) • Creates a map of habitat suitability (HS) using spatial data
Habitat Dynamics Program	• Allows calculation of time-series of carrying capacities and/or vital rates for each population. This can be used to model effects of changes in habitat over time.
Sensitivity Analysis	• Used to run several simulations of a metapopulation model, to analyze sensitivity of results to parameters. • Can be run manually (prepare several input files in advance with metapopulation program) or automatically (select main model and parameter, and specify changes in parameter for each run)
Comparison of Results	• Used to compare different metapopulation models by superimposing their results • Allows statistical comparison of different risk curves • Used to view results of a sensitivity analysis, to compare management options or assess anthropogenic impact

Output

Each of the five programs in RAMAS GIS has its own output data. Some of the data results in one program are used in calculations of another program. Tables 21–24 and Figures 8 and 9 give summary Spatial Data Program output that is used as input into other programs.

Table 21. Output summary for the Spatial Data Program.

Result	Description	Program(s) Applied To
Habitat suitability (HS) map (Figure 8)	Map of the suitability of the each location (raster cell) for the species being modeled	
Habitat suitability histogram	Frequency histogram of habitat suitability (HS) values (percentage of landscape in each habitat suitability category)	
Patch summary (for each patch)	Total suitable habitat, average habitat suitability, carrying capacity, initial abundance, maximum growth rate, relative vital rates, mean coordinates (of patch)	Metapopulation Program
Landscape indices (for each patch)	Patch area (#cells), patch area (km^2, ha), area as % of patches, area as % of landscape, core area, edge (km), edge:area (km^{-1}), shape index, fractal dimension	
Metapopulation map (Figure 9)	Simplified map of spatial structure of patches	Metapopulation Program
Populations	Coordinates, K, initial abundance, relative fecundity, relative survival (calculated by Find Patches)	Metapopulation Program
Distance matrix	The distance between each pair of populations, calculated by Find Patches	Metapopulation Program

Table 22. Landscape metrics from the Spatial Data Program calculated for the Fort Bragg, NC area.

Patch	Area (# cells)	Area (km^2)	Area as Patches	% of landsc.	CoreA (km^2)	Edge (km)	Edge: A (1/km)	Shape Index	Fract. Dimen.
1	14	14	0.25%	0.03%	1	18	1.286	1.203	1.14
2	20	20	0.35%	0.05%	2	22	1.1	1.23	1.138
3	10	10	0.18%	0.02%	0	16	1.6	1.265	1.204
4	18	18	0.32%	0.04%	0	26	1.444	1.532	1.295
5	15	15	0.27%	0.03%	0	22	1.467	1.42	1.259
6	9	9	0.16%	0.02%	0	14	1.556	1.167	1.14
7	10	10	0.18%	0.02%	0	9.2	2	1.581	1.398
8	207	207	3.66%	0.47%	132	80	0.387	1.39	1.124
9	14	14	0.25%	0.03%	0	22	1.571	1.47	1.292
10	4	4	0.07%	0.01%	0	10	2.5	1.25	1.322
11	13	13	0.23%	0.03%	1	18	1.385	1.248	1.173
12	34	34	0.605	0.08%	12	26	0.765	1.115	1.062
13	11	11	0.19%	0.03%	0	18	1.636	1.357	1.254
14	30	30	0.53%	0.07%	2	46	1.533	2.1	1.436

Patch	Area (# cells)	Area (km^2)	Area as Patches	% of landsc.	CoreA (km^2)	Edge (km)	Edge: A (1/km)	Shape Index	Fract. Dimen.
15	4	4	0.07%	0.01%	0	10	2.5	1.25	1.322
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
270	11	11	0.19%	0.03%	0	20	1.818	1.508	1.342
271	5	5	0.09%	0.01%	0	12	2.4	1.342	1.365
272	64	64	1.13%	0.15%	4	76	1.188	2.375	1.416
273	10	10	0.18%	0.02%	0	18	1.8	1.432	1.306
274	33	33	0.58%	0.08%	0	48	1.576	2.263	1.467
275	17	17	0.30%	0.04%	0	20	1.647	1.698	1.374
276	5	5	0.09%	0.01%	0	10	2.4	1.342	1.365
277	9	9	0.16%	0.02%	0	14	1.556	1.167	1.14
Sum	5657	5657	100.00%	12.88%	987	7122			
Average		20.4			3.6	25.7		1.502	1.31
Overall landscape indices							1.259	23.673	1.732

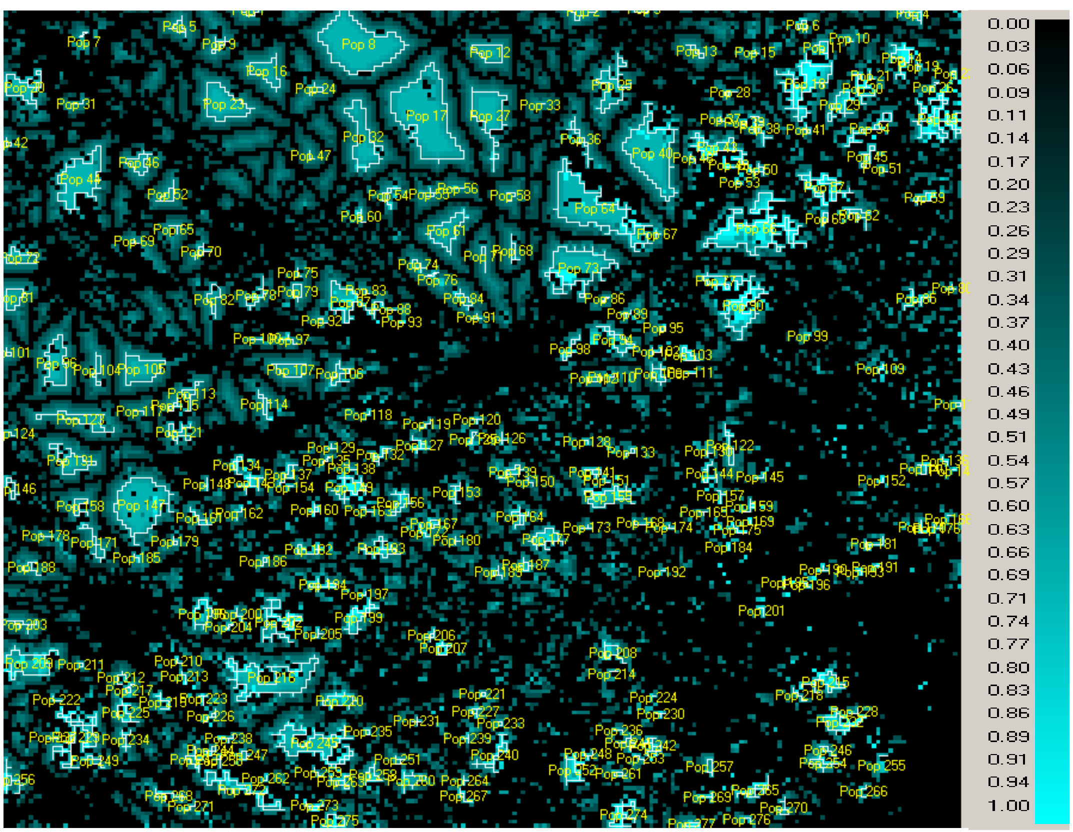


Figure 8. Habitat suitability map from the Spatial Data Program showing potential population locations for the Red-cockaded woodpecker near Fort Bragg, NC. Populations are indicated by the yellow circle and labeled with "Pop #."

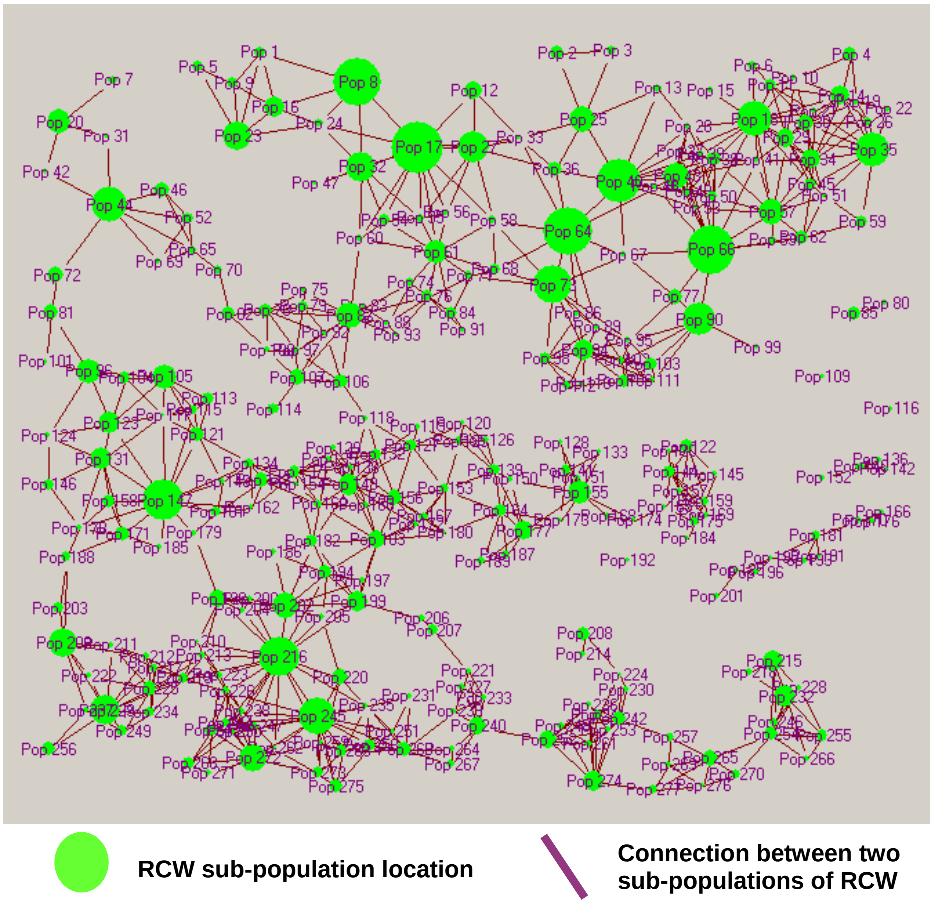


Figure 9. Metapopulation model from the file for the Red-cockaded woodpecker near Fort Bragg, NC.

Table 23. Output summary table for the Habitat Dynamics Program.

Result	Description	Program(s) Applied To
Metapopulation model file	ΔK, Δ relative fecundities, Δ relative survivals	Metapopulation Program
Patch dynamics*	HS map, patch map, HS map with patches, all HS maps, all patch maps	
* This is actually a result of the Spatial Data Program.		

Table 24. Output summary table for the Metapopulation Program.

Result	Description
Trajectory summary	Statistical summary of abundance of metapopulation through time, displayed with +/- 1 standard deviation
Harvest summary	Statistical summary of total weight of the harvest as function of time, displayed with +/- 1standard deviation
Risk of low harvest	Probability that a harvest will be at or below a range of abundances at least once during the next duration time steps
Population structure	Histogram of distribution of individuals among populations at any time step, displayed with average, +/- 1standard deviation, minimum, maximum

Result	Description
Final stage abundances	Histogram of distribution of individuals to different stages in any population, at final step of simulation, displayed with average, +/- 1standard deviation, minimum, maximum at each stage of specific population
Metapopulation occupancy	Statistical summary of occupancy of the metapopulation as it changes through time, shows changes in # extant populations, displayed with average, +/-1 standard deviation, minimum, maximum of extant populations
Local occupancy	Statistical summary of occupancy rate (proportion of time patches remain occupied); shows histogram with +/- 1standard deviation, minimum, maximum # time steps each population remained extant
Local extinction duration	Statistical summary of maximum duration of local extinctions (patch was unoccupied); result gives average, standard deviation, minimum and maximum
Interval extinction risk Terminal extinction risk	Risk that total metapopulation abundance will fall below a range of thresholds; interval risk means it occurs at least once, terminal risk means that it ends up below thresholds
Interval explosion risk Terminal explosion risk	Risk that total metapopulation abundance will exceed a range of thresholds; interval risk means it occurs at least once, terminal risk means that it ends up above thresholds
Interval percent decline risk Terminal percent decline risk	Probability that total metapopulation abundance will decline by a specific percentage from its initial value; interval means it occurs at least once in simulation; terminal means it ends up that way
Time to quasi-extinction	Distribution of times it takes the metapopulation size to fall below the threshold value of extinction
Time to quasi-explosion	Distribution of times it takes the metapopulation size to increase above threshold value of explosion

Sensitivity Analysis Program

This program allows multiple simulations to be run with the Metapopulation Program. It will perform a sensitivity analysis on specified parameters. To run the analysis, up to five input files must be run and saved, which can be input automatically or manually.

Comparison of Results

This program allows comparison of results from different simulations by superimposing results such as graphs of trajectory summary, metapopulation occupancy, etc (Figures 10 and 11). It also allows statistical comparison of different risk curves. It can be used to view results of a sensitivity analysis, to evaluate management options, to compare alternative methods, or to assess anthropogenic impact.

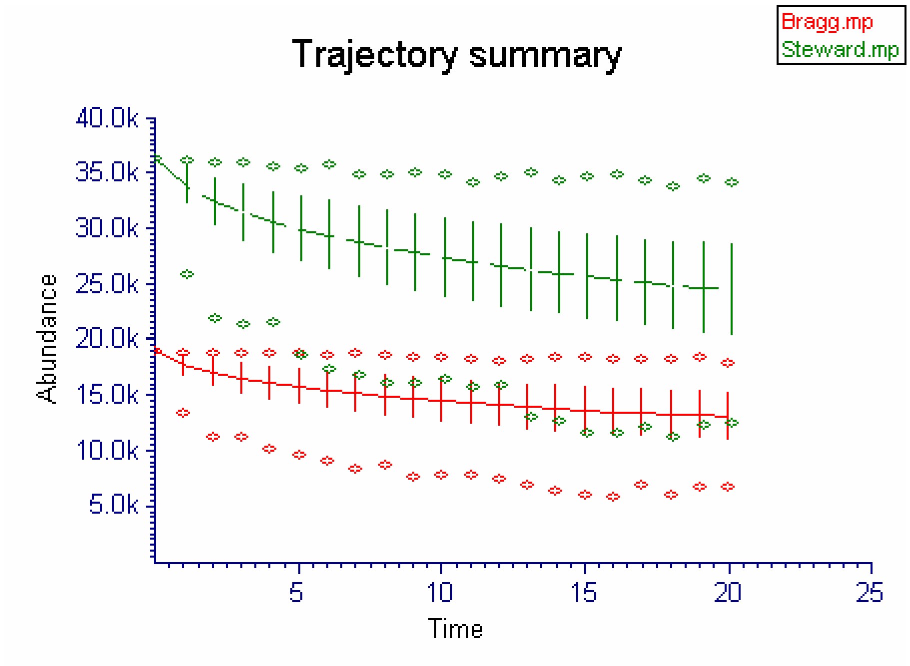


Figure 10. Example of a comparison of a result of the metapopulation program. This plot compares the Red-cockaded abundance trajectory summary for two locations, near Fort Bragg, NC and Fort Stewart, GA.

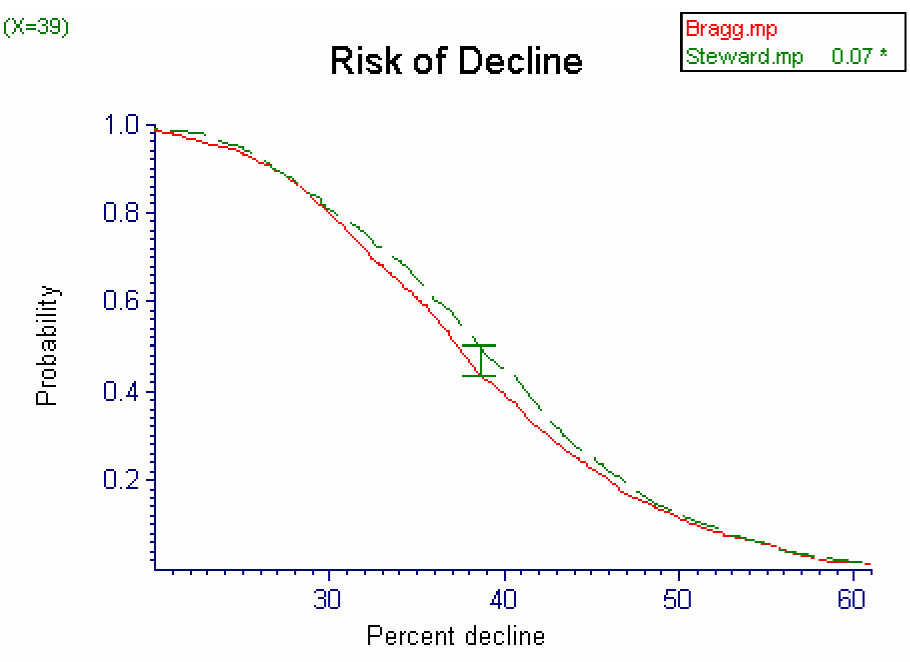


Figure 11. This graph compares the viability of the two populations in terms of expected percent decline any time in the next 20 years.

Input

RAMAS GIS can import several types of raster-formatted data. The data has two major requirements: all layers should be numerical, and all layers should describe the same piece of landscape with the same precision.

Resources Required

The RAMAS GIS program requires an IBM-compatible PC that runs a Microsoft Windows 95/98/2000/NT 4.0/XP operating system. RAMAS GIS can be run on a 486 processor, although a 100 MHz or faster processor is recommended. The program requires approximately 15 MB of hard disk space. The memory requirements depend on the operating system (Table 25).

Table 25. Resources required to run RAMAS GIS.

Operating System	Minimum Memory	Recommended Memory
Windows 95	16 MB	≥ 48 MB
Windows 98	32 MB	≥ 64 MB
Windows 2000	48 MB	≥ 104 MB
Windows XP	80 MB	≥ 168 MB

Technical expertise required

RAMAS GIS is designed for an expert familiar with metapopulation and GIS methods. An extensive manual detailing step-by-step operation and background of metapopulation dynamics is provided with the software.

Support

Table 26 lists several ways to obtain technical support directly from the model.

Table 26. Support for RAMAS GIS.

Area of Problem	Manual Reference	Program Reference
Using the program	Chapters 1, 2, 12	• Press “F1” while in input or result window • Press “F1,” click “Contents,” and read “Using…”
Modeling (general)	Chapters 7-11	• Look under “Introduction to Metapopulation Modeling”
All questions & difficulties	Refer to index	• Press “F1,” click “Index,” type in keyword • Press “F1,” click “Contents,” select “Frequently asked questions” in the help file

Users may also check the “frequently asked questions” at URL:
http://www.ramas.com/gis-faq.htm

Contact Applied Biomathematics at e-mail:

ramasgis@ramas.com

Versatility

RAMAS GIS can effectively model any landscape habitat and any species within that habitat. It has been applied to plants, invertebrates, fishes, amphibians, reptiles, birds, and mammals, in terrestrial, freshwater and marine environments (see examples under "Applications," p 12). The Oxford University Press will publish an edited book that includes RAMAS models for 37 species later this year.

Linkage Ability

RAMAS GIS accepts input from a wide variety of GIS programs. The program is also capable of exporting files for use in other programs.

Strengths

RAMAS GIS can model a species' response (in terms of population size or viability) to habitat change, as well as to other human impacts or conservation actions. Other models reviewed above can describe the landscape (FragStats, r.le, Patch Analyst), describe the suitability of a single habitat to a species (HSI), or describe the changes in landscape over time (CURBA, LUCAS), but none of them can translate a time series of habitats into a species' response.

Another strength of RAMAS GIS is its ability to link to models that predict landscape change. A recently developed addition, RAMAS Landscape, links the program to the landscape model LANDIS (which predicts forest landscape structure in terms of tree species composition and age classes). In principle, the program can be linked to any model that predicts the future landscape in the form of a time series of raster maps.

Shortcomings

The program allows only one-way interaction between the landscape data and the metapopulation model.

RAMAS GIS does not estimate the function that relates landscape data to habitat suitability or to the parameters of the metapopulation model. These functions need to be input manually, and must be estimated using logistic regression or some other method.

Input parameters are not estimated in this model; the user must research relevant literature and use that information to estimate input parameters. The RAMAS GIS manual does, however, provide the user with background information, simple examples, and references to the relevant literature.

RAMAS GIS (and in general, habitat-based viability methods) require more information than habitat suitability models, because they require demographic information in addition to habitat information.

Applications

The RAMAS GIS manual has an extensive bibliography on the use of the program in empirical studies (Table 27). This section summarizes three studies that used the RAMAS GIS program.

Table 27. Studies that have used RAMAS GIS.

Plant	Invertebrate	Amphibian/Reptile
Drechsler et al. 1999 Blumenthal and Jordan 2001	Akçakaya and Baur 1996 Sawchik et al. 2002	Berglind 2000 Griffiths and Williams 2000 Funk and Mills 2003
Fish	**Bird**	**Mammal**
Williams et al. 1999 Brown et al. 2001 Root 2002	Akçakaya and Atwood 1997 Root 1998 Wilson et al. 2001	Litvaitis and Villafuerte 1996 Broadfoot et al. 2001 Wielgus 2002

Root performed a study to look at the effects of habitat quality, connectivity, and catastrophes on the Florida scrub jay (*Aphelocoma coerulescens*), which is threatened by habitat modification and loss (Root 1998). The study focused on four subpopulations of the jay in southern Florida. The purpose of the study was to assess the long-term viability of the species. Population modeling was used to answer the following questions:

1. What effect does habitat quality have on the probability of extinction?
2. What is the likelihood of persistence, given field-surveyed habitat conditions?
3. How does the introduction of a natural catastrophe or epidemic affect long-term survival?
4. How does the spatial distribution of suitable habitat patches affect extinction rates?
5. Is dispersal among patches within a population critical for long-term viability?

To answer all of these questions, the author constructed a female-only, stochastic, six-stage population model in RAMAS Stage and a modified version of the model in RAMAS GIS. RAMAS Stage was used to examine the effects of habitat conditions

at the time of survey, gradually deteriorating habitat quality, and full, rapid restoration of habitat quality for each of four subpopulations of the Florida scrub jay.

The results showed that habitat quality is critical to the long-term viability of the Florida scrub jay in all four subpopulation locations but resent habitat quality will not support the bird for the next 60 years. Restoration of the moderately and severely deteriorated habitat would not be effective, instead, priority should be given to restoring the optimal and slightly deteriorated habitat and also being the least expensive plan. To preserve the Florida scrub jay (and other long-lived, slowly reproducing species):

- *Maintain adult breeders*. Focus on maintaining adult breeders, which, according to sensitivity analysis, has a large effect on population growth. Increasing the survival of the breeders will enhance population growth.
- *Restore habitat*. Restore and maintain habitat with the species' requirements in mind.
- *Connect patches*. Make and maintain connections between patches of suitable habitat. This increases dispersal, mitigates epidemic effects and may lead to colonization of a previously unoccupied habitat.

The second study was performed by Kindvall to look at dispersal in a metapopulation of the bush cricket (*Metrioptera bicolor*) (Kindvall 1999). The author developed a spatially explicit movement model to predict inter-patch dispersal rates for the study species. To test the hypothesis of patch-independent emigration rates, RAMAS GIS was used.

The hypothesis of patch-independent emigration rates is commonly used as an assumption in models of metapopulation dynamics. To test this hypothesis, the author incorporated estimates of inter-patch dispersal rates (obtained earlier in the study) into a structured metapopulation model. RAMAS GIS was then used to test the hypothesis by simulating local population dynamics according to a discrete logistic equation of population growth. Two different inter-patch dispersal matrices were tested in simulations, one with original rates predicted by the movement model and another where all inter-patch dispersal rates were standardized by the mean value of all predicted emigration rates. To calculate the expected number of inter-patch dispersers, patch specific estimates of male (disperser) population size were used.

The results of the study showed that the stochastic movement model developed was capable of predicting emigration rates of the bush cricket from specific patches of different size and shape with "acceptable" precision. However, as individual movement behavior is affected by landscape composition, the stochastic movement model fails to predict dispersal patterns on a landscape level.

After testing with RAMAS GIS, the patch-independent hypothesis described above was rejected. This has implications for metapopulation theory, as patch-dependent emigration may affect extinction probabilities of local populations. This is because patch size affects local extinction rates through its impact on emigration (there is a negative association between patch size and emigration rates). Therefore, inter-patch dispersal is high enough to compensate for emigration loss in large patches, while small patches receive too little immigration to be rescued.

Akçakaya & Atwood used RAMAS GIS to develop a habitat-based metapopulation model for the California gnatcatcher in central and coastal Orange County (Akçakaya and Atwood 1997). The study had three goals: (1) to develop a habitat suitability model for the California gnatcatcher, (2) to demonstrate how the model could be linked to a metapopulation model for viability analysis, and (3) to analyze the sensitivity of the viability of the gnatcatcher to uncertainties in model parameters.

To accomplish the study goals, RAMAS GIS was used to link landscape data with the metapopulation model. Logistic regression was used to calculate the habitat suitability function, which was then used to calculate an index of habitat suitability for each cell in the grid file. Vital rates of the gnatcatcher population, such as carrying capacity, initial abundance, and fecundity (among others) were estimated from demographic data.

To predict the viability of the metapopulation, three measures were used: (1) median time to fall below the metapopulation extinction threshold, (2) risk of falling below the metapopulation threshold any time within 20 years, and (3) risk of falling below the metapopulation threshold any time within 50 years.

The results of the model simulations predicted a fast decline in gnatcatcher populations, with a high risk of extinction. However, due to the uncertainties in most parameters, the conclusion that the gnatcatcher metapopulation is threatened with extinction was not considered appropriate.

The habitat suitability function that resulted was validated using three methods. Each method concluded that the function is a good estimate of the quality of habitat in occupied locations. However, the function does have a weakness in that there is no data to support or refute the suitability in several locations.

Although there were several uncertainties in the model parameters, the study was useful. A sensitivity analysis provided information about which parameters need to be prioritized in study, for more careful estimations. Also, while the viability analy-

sis was not used in absolute terms, it is useful for ranking management options in terms of their predicted effect on the viability of the species.

Effective Area Model (EAM)

Source

Developers:	
	Barry R. Noon (Principal Investigator)
	Thomas D. Sisk (Principal Investigator)
	Haydee M. Hampton (Programmer)
Contact:	E-mail Haydee.Hampton@NAU.edu
Web site:	http://www.nau.edu/~envsci/sisklab/research_projects/EAM/index.htm
Use:	Install as extension to ArcView GIS

Overview

The Effective Area Model (EAM) was designed to provide a predictive tool for linking field and remote sensing data in a landscape model, to permit comparison of the impacts of alternative management strategies. The EAM is an extension to ArcView GIS, adding a menu called "EAM" to the menu bar of the View graphical user interface. It uses quantitative measures of species-specific edge effects to weight habitat quality within a patch, based on distance from the edge. The model then calculates an "effective habitat area" for each habitat patch within the study landscape or management area. This enables the prediction of changes in species' density and abundance given changes in landscape pattern.

Two classes of input data are required for the EAM, a detailed habitat map and the species density response to habitat type and distance from edges. EAM is a raster-based spatial model that is created by applying the animal density response to the closest patch edge. The EAM then provides a rapid, automated means of assessing effects of shifts in patch size, shape and edge characteristics, given a relatively small set of assumptions regarding species' response and the spatial relationship of its habitat.

Output

The EAM output is ArcView grid files and database files. The grid files indicate effective habitat area with animal density for the target species (Figure 12). One can generate an error grid using a user-defined confidence interval (%); the standard confidence interval formula is used in the calculation, and assumes normal distribution of the response variable.

Database files give summary statistics, including maximum, minimum, range, mean, standard deviation, sum, population and total population. They are formatted as dBase files, which can be easily exported to another spreadsheet program (such as Excel) for analysis (Figure 13).

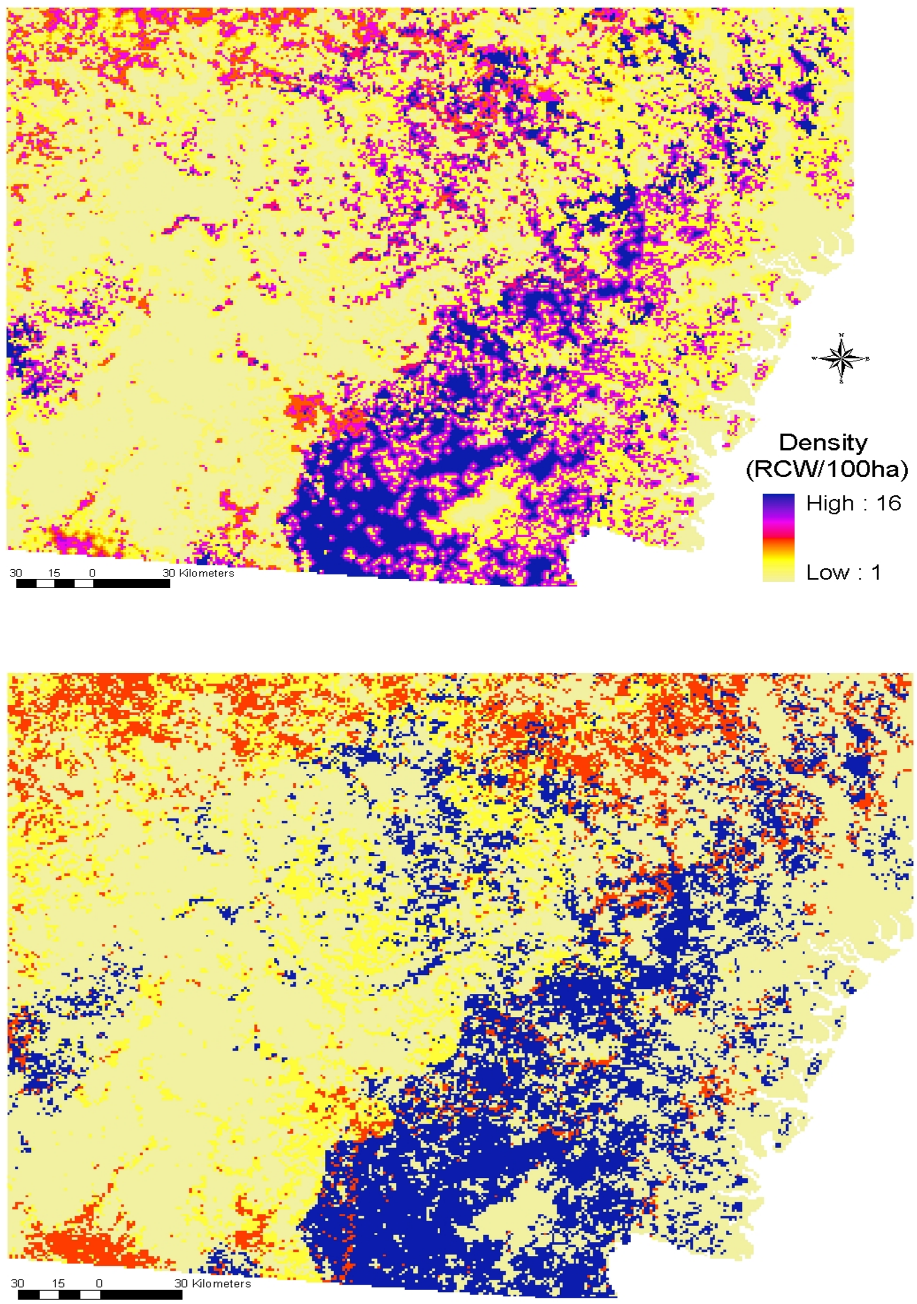
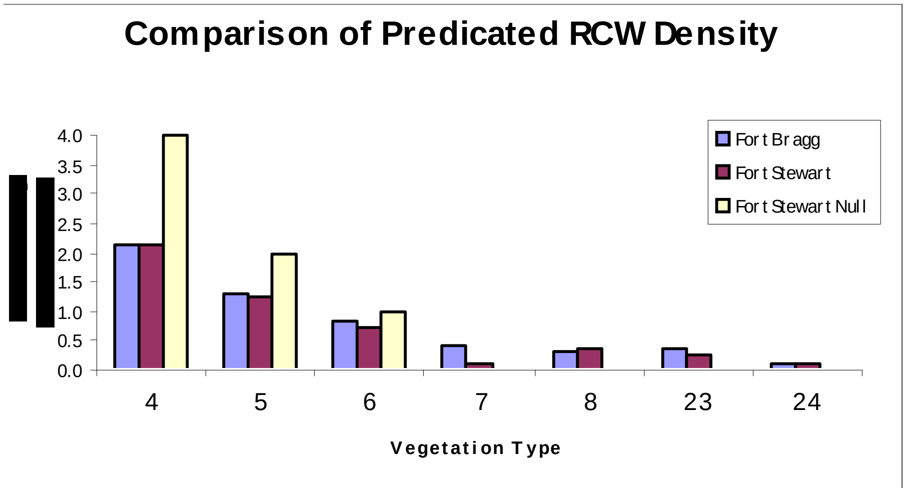


Figure 12. Example of EAM density grids using the edge response and no edge response (null) models for the Red-cockaded woodpecker near Fort Stewart, GA.



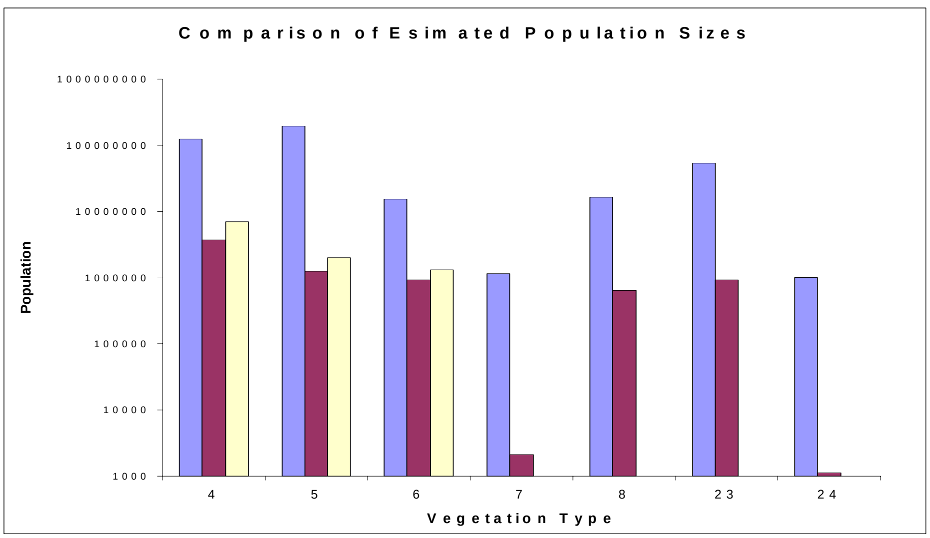


Figure 13. Example of the types of plots one can generate using the predicted density and population information generated in the EAM. Information is saved in a dBase file, and includes density information with summary statistics and a population estimate. Data is for the Red-cockaded woodpecker near Fort Stewart, GA.

Input

The EAM requires habitat spatial data (vegetation, elevation, etc.) and functions describing the change in animal density with distance from edge. The habitat spatial data must be a projected integer grid file or polygon shapefile, to be imported into ArcView GIS version 3.1 (or 3.2). The species' density response functions can be either linear or non-linear, using distance to edge as the only predictor variable.

Resources Required

The EAM requires a system with a Pentium II 266 MHz (or equivalent) with 32 MB of memory. A Pentium II 400 MHz with 64 MB of memory and a fast (<8ms) hard drive is preferred. The software requirements for the model are ArcView GIS 3.1 or 3.2 with the Spatial Analyst extension. EAM can be supported by Windows 95, 98 or NT.

Technical Expertise Required

To operate the EAM, one must have experience with ArcView GIS and manipulation of geographic data. For further analysis of database results, one must be familiar with spreadsheet and/or statistical software.

Support

Support for the EAM can be obtained by contacting the programmer, Haydee Hampton, at e-mail:

Haydee.Hampton@NAU.edu.

Versatility

The EAM extension allows modeling of any target species in any landscape, provided that you have the extensive data required.

Linkage Ability

Input data for the EAM is a specific format, namely ArcView grid files or shapefiles. Data must also be projected, or have information in the source/attribute table to enable projection by ArcView. One could use ASCII files for this purpose as well.

For output files, the animal density response is given in a grid file. The attribute table for that file may be exported to dBase for use in any spreadsheet program. The summary statistics are already given in dBase format.

Strengths

This model incorporates habitat and species density response information into one program for analysis. The program calculates the species' density and abundance response to the habitat given, and can therefore be used to assess impact of habitat change to a given species. However, this is provided one has habitat data for a time series or can manipulate habitat data to generate habitat change information.

The program can also "remove noise" from the habitat data. This function allows the user to remove habitat patches that are smaller than the user-specified area or number of pixels, and replace them with values of the patches' nearest neighbors. EAM can also classify "no data" fields to values of their nearest neighbors.

The program is able to calculate empirical error through calculation of confidence intervals. Error of the animal density grid is calculated to a user-specified confidence interval, assuming the response variable is distributed normally.

Shortcomings

The program emphasizes "effective area" which is a generalized version of the core area concept. Although this generalization is very useful, effective area (or core area) is only one factor that determines TES persistence in a landscape. Other factors (species' vital rates, predation, competition, climate, etc.) are not considered by this method. Also, EAM assumes habitat is static, and does not incorporate habitat dynamics (these limitations apply to all habitat suitability models).

Unlike some other methods of habitat suitability modeling, EAM requires prior definition of "patch" and identification of "edge." Other methods (such as HSI, or the more general methods of habitat modeling) do not require this, but if such information is available, these more general methods can be used to estimate the same functions (e.g., of distance to edge) that EAM uses.

Another shortcoming is that, unlike more general habitat modeling methods, EAM does not estimate the parameters of the function (e.g., based on occurrence data). Thus, using EAM requires using these more general methods (such as logistic regression) to estimate the parameters to enter in EAM. Although these inputs make logical sense, there is little fieldwork to support their generation for the EAM.

Applications

The EAM has been applied to two studies (Table 28). The program developer(s) conducted both studies.

Table 28. Studies that have used EAM.

Plant	Invertebrate	Amphibian/Reptile	Fish	Bird	Mammal
	Hampton et al. 2001			Sisk et al. 1997	

Both studies using the EAM tested the same thing on different organisms (Sisk et al. 1997; Hampton et al. 2001). Therefore, The following section summarizes the general use of the EAM as it applies to a target organism.

The two studies addressed two questions:

1. How does the habitat surrounding a given patch influenced the composition and organization of the species it supports?
2. How consistent are the population-level responses of the target species to different edges of similar types?

For the species-specific edge responses, extensive field data was collected on the target species abundance, as well as life history characteristics (to *infer* response) and abiotic factors such as microclimate. It should be noted here that for some species, the edge responses are well documented, so the collection of data can be limited to abundance and abiotic factors.

Once the edge responses were inferred for each species, the landscape imagery was classified and used to develop an effective habitat area. The EAM was then run both with edge responses as a factor and without (null model).

The results of both studies showed that the EAM predicted target species abundance well using the edge responses; the null model simulations did not accurately predict abundance in either study. In addition, the Sisk et al. study showed that the responses and abundance varied significantly according to the type of edge (woodland-grassland vs. woodland-chaparral); results between similar edges also varied, but only slightly. Both studies concluded that the responses of animal species to habitat edges might greatly influence their distribution in heterogeneous landscapes. This is very valuable in land management issues, where decisions often hinge on boundary management factors (reserve design, delineation of timber and grazing, etc.).

The DIAS RCW (Dynamic Information Architecture System Red-cockaded Woodpecker) Model

Source

Developer:	Chris Rewerts
Contact:	Chris.Rewerts@us.army.mil
	(217) 373-5825
Use:	Install DIAS and RCW Model

Overview

This model is the implementation of an object-oriented, agent-based, spatially explicit simulation of the Red-cockaded Woodpecker (*Picoides borealis*) (RCW). The goal of this model is to provide a tool for Army land managers who must balance the

military training mission with the protection of the RCW. The model tried to represent entities and processes as they are understood in the real world. It is an agent-based population model of a TES, the Red-cockaded Woodpecker, which includes aspects of the environment such as the spatial locations of nesting habitat and human management activities. This spatially explicit model takes advantage of GIS data and functionality.

A dynamic RCW population model developed separately by Lechter et al (1998) was implemented within DIAS (Dynamic Information Architecture System) as the first step in providing a flexible, robust simulation tool. The Agent-Based Model (also known as the Individual-Based Model) approach was chosen for implementation over a more traditional aggregate population modeling approach because of its ability to: (1) describe the population traits with distributions rather that mean values, (2) represent agent performance and local interactions, and (3) provide a mechanistic rather than a descriptive approach to modeling (DeAngelis and Rose 1992). Furthermore, the model described by Letcher et al. is spatially explicit, accounting for the importance of spatial distribution to RCW population dynamics.

The dynamic behaviors (or processes) described in the Letcher et al.(1998) model were broken out into five distinct "submodels" for implementation in the DIAS RCW application: breeding, competition, dispersal, fledgling role change, and mortality. These "submodels" address specific behaviors (DIAS "Aspects") of specific classes of objects (DIAS "Entities").

DIAS RCW used Lechter's model by capturing individual birds, their population groups and their territories as object entities, and by assigning separate, specific properties and behaviors to each entity.

The Entity object classes developed for the RCW application (RCWIndividual, RCWTerritory, RCWPopulation) contain the attributes that describe the state of the environment throughout a simulation. These Entities also contain links to the processes via their Aspects.

It is argued that one of the most important management actions to improve the success of RCW populations is the use of recruitment clusters—the creating of nesting habitat through the use of artificial nest cavities in trees. A submodel of the RCW behavior model (already developed) allows simulation of this management activity.

Output

It is possible to obtain from the model output for the status of the primary objects for the classes of the RCW individual, the RCW territories, and the RCW popula-

tion. For example, for each individual bird object that existed in a model run, each detail about it can be obtained. This can also be obtained dynamically, if using the Graphical User Interface (GUI), this information can be interviewed by clicking on object's icons displaced on the map, or by use of dynamic strip charts or graphs. In addition, output files are created (these are also configurable with moderate difficulty). An additional aspect of output was created to account for the inherent stochastic nature of the model. In other words, since when the model runs a given scenario (and the results are not going to be exactly the same if it runs it a second time), a mechanism is available to allow for running the same scenario any number of times and then for aggregating results.

Input

The DIAS RCW program requires a set of inputs (Lechter et al. 1998):

- for each gender, and each social role (breeder, floater, fledgling, solitary and helper), the annual mortality rate as a proportion between 0 and 1
- the speed of dispersal for male and female fledglings and floaters, in km/yr
- proportion of male fledglings dispersing, as a value between 0 and 1
- search range for dispersing males and females, in km
- initial demographic composition of clusters, including bird ID, gender, age, role, and territory ID
- cluster/territory data, including territory ID, geographic coordinates, and status (active/inactive)
- parameters to describe fecundity using installation data
- transition probabilities for changes in social status.

The specific parameters used to describe mortality, dispersal, and fecundity are:

- mortality
  - male fledgling annual mortality
  - male floater annual mortality
  - male helper annual mortality
  - male solitary annual mortality
  - male breeder annual mortality
  - female fledgling annual mortality
  - female floater annual mortality
  - female breeder annual mortality
- dispersal
  - proportion of male fledglings dispersing
  - male fledgling disperser speed (km/yr)
  - male floater disperser speed (km/yr)
  - female fledgling disperser speed (km/yr)
  - female floater disperser speed (km/yr)

- female disperser search range
- chance of leaving in season 2
- chance of leaving in season 3
- chance of leaving in season 4

- fecundity
  - nest failure model intercept (b0)
  - nest failure male effect (b1)
  - nest failure female effect (b2)
  - nest failure helper effect (b3)
  - mean fledgling model intercept (b4)
  - mean fledglings male effect (b5)
  - mean fledglings female effect (b6)
  - mean fledglings helper effect (b7)
  - female nesting attempt parameter (a)
  - re-nesting probability.

There are a number of options on the mechanics of running the model. The model can be run using a GUI that includes options for dynamic map display of the land area, the territories, and individual birds. Colored icon shapes identify territory location and status, bird role, and their locations and movements. The user can interrogate all objects by interacting with the map/GUI display. The user can set up charts to show progress/change of any object in play either during processing of the simulation or can replay results after the simulation has processed. The simulation can be run without the GUI, e.g., in command line mode. There is also the capability to run in a batch model where parameter values for each run in the batch is controlled by a line in a file, for instance, this is useful when conducting a sensitivity analysis of parameters. In such a case inputs can be created in a spreadsheet or other tool and then run by the model.

Resources Required

The DIAS RCW model can run under Windows (2000 or XP), Mac OS X, or Solaris 10 Operating systems. Depending on the number of objects in the simulation, the number of years being simulated, the number of iterations of the scenario being run, and other similar factors, the processing time can be improved by additional memory and processor speed. The DIAS RCW is equipped with the option of using Java Remote Method Invocation (RMI), so that the simulation processing can be shared among other computers on a network.

Technical Expertise Required

To use DIAS RCW model, knowledge of the behavior and demographics of the individual species is required, as well as an understanding of the required input data and parameters. The system comes with an installer package to ease that aspect of usage. A graphical user interface eases the use of the system, but there are aspects of data manipulation that will challenge novice computer users. The quality of the interpretation and analysis of the model results, as well as applying the model results in a management or other context, are not automatic and it is necessary that the user be able to understand the abstractions of the model assumptions and how it projects these on the artificial landscape to best make use of the model as a tool.

Support

The DIAS RCW model is not currently publicly distributed, however an evaluation version, with an artificial data set, can be made available from the author listed above. DIAS intellectual property is protected in part under a U.S. Patent by the University of Chicago, as operator of Argonne National Laboratory for the U.S. Department of Energy. The existing DIAS system, as well as any improvements and modifications to that system under the proposed research, are and will be freely available to U.S. Government agencies and their contractors. Under the terms of a U.S. Government purpose license, agencies and their contractors are permitted to use DIAS intellectual property royalty-free, under a paid-up, nonexclusive, irrevocable worldwide license, with the rights to use and reproduce the software and to prepare derivative works. Argonne has agreed that Federal users of DIAS that produce derivative systems have a perpetual, royalty-free license to use and distribute for free DIAS binary software, non-Java source code with supporting development files (e.g., makefiles), and documentation. Any non-Federal group that uses DIAS outside of working for a Federal agency or sells a product containing DIAS would require an explicit license from Argonne National Laboratory.

Versatility

The DIAS RCW model framework provides the option of including models developed by other people, even if the other model was written in a different programming language or ran on a different computer on the Internet. The model was designed so that integrating other models or more of our own sub-models could be updated through time without requiring a complete overhaul of the system.

Linkage Ability

The DIAS RCW model was designed to allow modification of the existing objects and behaviors in the model, plus integration of different submodel and support program as the understanding of the species increased over time. The DIAS environment for simulation and integration of models is extremely powerful and flexible, allowing the modification of objects and behaviors and the integration with other models. For example, the representation of habitat in the RCW model is sparse; only the locations of the nesting habitat are represented. There is a version of the model under development wherein a forest dynamics model (including separate submodels for forest growth, pathology, and management) for an Army installation that desires to understand how scenarios of forest management plans may change the habitat over time, and thus use this, integrated with the RCW model, to determine how the ensuing pattern of available forage and nesting habitat simulated over time may effect the RCW population.

Strengths of the RCW Model

The DIAS RCW model was designed to capture the characteristics of a single TES species, the RCW. In this manner, it adopted the basic characteristics and structure of the most widely respected RCW model available (Letcher 1998). One of the unique aspects of the RCW is that it nests in living pine trees, which need to be of a minimum size and age to be suitable. In addition, considerable energy and time on the part of the RCW are required to establish the nest cavities. These factors combine in such a way that suitable nesting habitat can be limited, can take many years to establish, but once occupied can remain occupied for relatively long periods. The basic RCW model, therefore, focuses strongly on this aspect of the RCW, as the spatial distribution of a population's nesting sites is very important. Thus the inputs are tailor made for a specific TES species of high interest to the military. This is unlike any of the other modeling packages reviewed here. It also represents the presentation of the model itself as a public domain capability so that it can be investigated cooperatively among a variety of agencies.

Strengths of the DIAS Approach to Ecological Modeling

The primary goal during the creation of the DIAS RCW simulation framework and models were to enable and improve decision support for Army land managers through the use of modeling to simulate ecological processes of concern based on best science available. To do this, it was built upon a flexible software infrastructure that offers the ability to:

- address a complex problem by allowing many disparate multidisciplinary simulation models and other applications to work together harmoniously within a common framework
- integrate existing legacy-type models without extensive reworking, thus capitalizing upon previous investments in already available models and applications
- provide an integrated architecture that allows for the ability to reflect the dynamics of real-world systems
- encourage the development of object libraries that contain a large number of reusable objects to represent a wide variety of real-world elements and therefore reduce the long-term cost of redeveloping objects and technologies
- support software applications that can operate at multiple spatial and temporal scales
- incorporate new data, concepts, and technologies that will bring the best available knowledge, science, and technology to bear on decisionmaking processes
- operate in a distributed environment where applications can be linked across multiple machines via computer networks.

Shortcomings

The use of DIAS as the framework puts this model at the forefront of TES modeling technology, however it usually follows that the most powerful tools are also the most complex. That being said, while most models are designed and built to be run by modelers, the philosophy behind the design of this model was to create a tool that could be used by Army land managers to augment their decisionmaking. It was built based on the more academic versions of models published in the literature, but it has not been rigorously tested and validated as might a more academic model.

Since it is still in the development phase, and most of that funded as an on-the-ground tool by the intended users, it has had more of a practical application focus for that use, and thus the intended public domain nature of the model has not yet been realized. Further, the objective of the model is to represent the behavior of a single TES. Although it has been structured to be highly versatile, whether it can be modified to represent the behavior of other TES remains to be implemented. The current work to more fully represent the dynamics of the species habitat, the mature pine forests, is nearly ready for testing, but will be most relevant to the location for which it has been funded to serve.

Applications

The DIAS RCW model has not been used in a variety of studies; in fact no references in the juried literature yet exist for the model. The current operational versions are in use by Fort Benning, GA. The most recent work focusing on a system customized to explore forest dynamics, including growth, pathology, and management of forested areas of Fort Benning that are now or potentially could become RCW habitat.

3 General Evaluation of the Models in Relation to Military Lands Management

This chapter presents a general overview of the models evaluated in this project, and evaluates the different model types in relation to military lands management, particularly from the point of view of modeling the effects of fragmentation on TES.

The models can be grouped in four categories:

1. Index methods
2. Habitat suitability models
3. Landscape prediction models
4. Species viability models.

Each category contains models that were not part of the review, but are nonetheless mentioned briefly in this general evaluation (Table 29).

Table 29. Characteristics of fragmentation models.

	Index methods	Habitat suitability models	Landscape prediction models	Species viability models
Evaluated models	• FragStats • r.le • Patch Analyst • (HAMS)	• HSI • HAMS • EAM	• CURBA • LTM • LUCAS	• RAMAS GIS • DIAS RCW
Other models		• GLM (general linear models) • GAM • Artificial neural networks • Genetic algorithms	• SLEUTH • UrbanSim • LANDIS • LEAM	• Vortex • ALEX • RAMAS Landscape

Index Methods

The methods in this category (FragStats, r.le, Patch Analysts) calculate a variety of patch and landscape-level metrics or statistics that characterize the spatial structure of the landscape. These metrics include measures of area (e.g., mean patch size), shape (e.g., fractal dimension), isolation (e.g., nearest neighbor distance), and other attributes of predefined patches (of specific types) distributed in a landscape.

The three programs do a very good job of making these calculations relatively easily. A fourth program (HAMS) also calculates some landscape metrics, but it is reviewed below under habitat suitability models. However, there are four primary shortcomings of the index methods as a tool for analyzing the effects of habitat fragmentation:

1. The index methods are based on pre-defined patches or habitat categories. To be useful in habitat fragmentation assessment, the definition, and the spatial scale of patches must be determined for a particular species before the analysis. This would require a habitat analysis for the species (e.g., with the habitat suitability models discussed below), and considerations of behavioral characteristics of the species (territoriality, home range, dispersal, etc.) that affect its use of space. In other words, the patches must be defined (or, the landscape must be "interpreted") from the point of view of the species in question, because different species (even those that are dependent on the same habitat types) can perceive the landscape in different ways, depending on their behavioral characteristics, dispersal ability, etc. A related issue is that the important habitat variables for any particular species are often not limited to landscape metrics (such as patch size), but almost always include habitat variables related food availability, nesting location, climate, and disturbances.
2. Index methods describe the structure of the landscape, but do not analyze the effects of habitat structure on floral or faunal species. The relationship between the metrics reported by the index methods, and the biological response of the species (e.g., its density, abundance, survival, and persistence in the landscape) must be quantified using other methods (such as PCA, or regression). This would require determining the biological variable (such as abundance, survival, fecundity, etc.), and collecting spatially explicit data on this variable. Note too, that even analysis of species using these methods will only account for landscape metrics, and does not take into consideration variables such as food availability, microclimate, etc.
3. The types of analysis described above can be used to find relationships between landscape metrics and population responses, but it is difficult, if not impossible to use these relationships for predictive purposes, e.g., to predict the future population responses in the same landscape, or the population responses in another landscape, or the response of another species. The reason for this is that there are no general relationships between landscape indices and the persistence of populations inhabiting the landscape. In specific cases, the relationships vary with species, with landscape, and with the spatial scale.
4. The index methods are static; they do not consider or model temporal dynamics (e.g., changes in land use). If future landscapes are predicted using another program (e.g., the landscape prediction models discussed below), the index methods can be used to calculate the changes in landscape metrics.

In summary, the three index methods evaluated can be equally useful in quantifying spatial structure, but their utility in predicting or evaluating effects of habitat fragmentation on threatened and endangered species is very limited.

Habitat Suitability Models

The methods in this category (HSI, HAMS, EAM) are used to predict a species' response to its environment, including the landscape it lives in. The response is usually the occurrence or abundance of the species at a certain locality or the carrying capacity of the habitat. The model is usually in the form of an equation that relates this response to various habitat-related variables. These variables can include landscape metrics, as well as other variables that determine the suitability of the land as habitat for a particular species (such as elevation, basal area for particular tree species, distance from roads, distance from water, etc.). The model is often used to calculate a habitat suitability (HS) map for the species.

Unlike the three index methods evaluated above, these three methods are quite different from each other, as well as from other habitat suitability models that were not evaluated. The HAMS model is based on pattern recognition (PATREC) method, which is not widely used and can lead to over-fitting. The EAM model can be useful in the limited context of edge effects, but other, more general habitat suitability models can also incorporate such effects. In addition, the HAMS and EAM models are not widely used, and there are very few examples of their application. Thus, these models are not recommended.

The HSI method is widely used, very simple and straightforward. However, the variables selected for inclusion in the HSI model, and the shape of the function for each variable, are usually based on expert opinion and can therefore be subjective. In addition, the form of the function is restrictive and arbitrary, does not readily allow for interactions between variables, and often requires assumptions of linearity between a habitat variable and the species' response to the variable.

These particular shortcomings of the HSI model can be reduced or eliminated by the more quantitative and objective methods of habitat modeling, such as general linear models (e.g., logistic regression, also known as resource selection function, rsf). These statistical procedures use species occurrence or abundance at each location as the dependent variable and the habitat characteristics as the set of predictive variables. Most statistical methods require both presence and absence data, while others (such as "climatic envelopes") require only presence data (Elith 2000). The advantage of these statistical habitat suitability models over the HSI model is that

they are statistically rigorous and can be validated; they can also incorporate nonlinearities of, and interactions among habitat variables.

There are also other advanced methods (artificial neural networks, genetic algorithms, decision trees) that can incorporate nonlinearities and interactions. However, these methods are not recommended because their results are often not very different from the more traditional methods such as logistic regression, but their use requires considerably more expertise.

Because the habitat suitability models relate features of the landscape to its use by particular species, their output (habitat functions or habitat maps) are relevant for the questions related to managing lands, particularly for studying the effects of fragmentation on TES. The models that are based on statistical methods are especially relevant, because they are objective, and can be validated. These models can be used to estimate habitat functions (and to create habitat maps) at different time steps, provided that both landscape data (maps of land cover, etc.) And occurrence data are available for multiple time steps. Such time series of habitat maps can be used to monitor the change in species' habitat.

Although the results of these models show them to be relevant to land management decisions, they cannot be used by themselves to make such decisions because of several shortcomings.

The fundamental shortcoming of all habitat suitability models is that they describe habitat suitability, but they do not predict the viability or persistence of the species in that habitat, because viability also depends on factors other than habitat suitability, including landscape-level factors (e.g., expected future change in the amount and spatial distribution of habitat) and demographic factors (survival, fecundity, and dispersal as functions of habitat; exploitation and other impacts not related to habitat, etc.). In other words, habitat suitability is only one component of viability, thus, it cannot be used by itself to predict the effects of fragmentation on the future persistence of TES in a given landscape. Thus, it is recommended that statistical models of habitat suitability (esp. Logistic regression) be used in combination with viability-based methods.

Another important shortcoming of habitat suitability models is that they treat habitat as a static component, and do not incorporate dynamic changes in the landscape. Depending on the landscape, and the specific fragmentation question to be addressed, this may be an important shortcoming. For those cases where the temporal change in the spatial structure of the habitat is important, general models of habitat suitability can be (and have been) linked to landscape models (see "Landscape Prediction Models," below).

Landscape Prediction Models

These models aim at predicting the future of a landscape in terms of land use and land cover. Thus, they do not directly predict impacts on TES, but by combining them with habitat models (above) and viability models (below), the effects of landscape change on TES can be evaluated. However, this has been done only to a limited extend (see below).

There are a large number of landscape prediction models. The three reviewed models (CURBA, LTM, and LUCAS) belong to a large group of at least 20 models (most of them recently reviewed by Agarwal et al. 2002). Other examples of this type of model include SLEUTH (http://www.ncgia.ucsb.edu/projects/gig/) and UrbanSim (http://www.urgansim.org). These models focus on urban growth and other forms of human land use, but do not include much biological detail. For example, the natural vegetation is often categorized into very broad classes such as “forest” or, at most, “deciduous forest.” This lack of specificity means that these models cannot be used to predict the effects of human land-use on specific TES.

Another group of landscape models focus on predicting the changes in structure and composition of the vegetation cover or more general changes in classes of land cover. A widely used example of this type of landscape model is LANDIS (Mladenoff et al. 1996; Mladenoff & He 1999). The landscape models that emphasize vegetation change largely evolved from the early forest simulation models of the 1970s (Botkin 1972; Ek & Monserud 1974) and the first generation of models of spatial landscape change of the 1980s (e.g., Sklar et al. 1985). Today, a variety of approaches to spatial simulation of vegetation change exist (Mladenoff & Baker 1999); they vary in the ecological processes they simulate (e.g., succession, disturbance), their spatial resolution (cell size), and the extent or total landscape area they may simulate (10s to 1,000,000s of hectares). In general they include more biological detail than landscape models that focus on human land-use. For example, LANDIS simulates all age classes of up to 20 tree or shrub species in each cell. However, the models that focus on natural vegetation dynamics have limited capabilities for incorporating human activities other than timber harvest. Thus, they do not explicitly recognize and integrate land-use changes, particularly increasing urbanization.

Because they include more detail on vegetation structure, these models have previously been linked to habitat suitability models for particular species, including TES (Smith 1986; Davis & DeLain 1986; Hyman et al. 1991; Pausas et al. 1997; Curnutt et al. 2000; Akçakaya et al. 2003). Such links between landscape and habitat suitability models eliminate one of the shortcomings of habitat models (static landscape). However, the more important shortcoming of lack of direct relevance to persistence requires links with species viability models discussed below.

Species Viability Models

These are population or metapopulation models that simulate the dynamics of a species and predict its future in terms of number of individuals, risk of decline or extinction, and chance of recovery. Species viability models are based on population-level ecological models, including structured (life history, or matrix) models, individual-based models, and metapopulation models (Pastorok et al. 2002). From the point of view of evaluating the viability of species under fragmentation, the relevant types of population-level models are stochastic models with explicit spatial structure. There are several such models that are implemented as generic computer programs, including RAMAS GIS, Vortex, and ALEX. Lindenmayer et al. (1995) reviewed earlier versions of these programs. RAMAS GIS is the only one of these models that allows an explicit link to geographic information systems (GIS) software, and that incorporates dynamic spatial structure, including appearing, disappearing, merging, and splitting patches (Akçakaya 2001, Akçakaya 2002). RAMAS GIS also links the habitat suitability models discussed above to a species viability model. The habitat suitability model can be of a variety of types, including HSI model, or more general models such as logistic regression. However, the program does not estimate the habitat model; the user must enter the habitat model as a function.

Species viability models that have explicit spatial structure directly relate to the question of the persistence of a species in a fragmented landscape; thus, they are relevant to the issues related to managing lands. In addition, they can be used in a temporal manner to follow changes over time, and they can recognize and integrate land-use changes such as urbanization, if such changes are input as a time series of maps. However, species viability models, including RAMAS GIS, do not predict such maps, although RAMAS GIS can use such predictions as input, if they are exported as a set of (a time series of) raster maps describing the habitat variables that are used in the user-specified habitat suitability function. Thus, species viability models can be linked to landscape models by using the output of a landscape model as input for a spatially explicit (and spatially dynamic) viability model. An example of how such a link can be formed is a new program, RAMAS Landscape, which links the forest landscape dynamics model LANDIS to RAMAS GIS. This program integrates landscape and metapopulation approaches, allowing the modeling of species viability in a dynamic landscape.

Relative Costs

It is difficult to estimate the relative costs of the various types of models because most of the cost of using a model is in applying it to a particular situation or ques-

tion in a particular landscape. Costs of application are in general much more than costs of implementation and maintenance, which are in turn much more than the cost of acquisition.

Implementation and maintenance can be more costly for some models, depending on the type of computer hardware and software already available. In general, Windows-based software cost a lot less to implement and maintain, because of the general availability, and the relatively low cost of required hardware and software.

Costs of application depend on the type of data that is available and the degree to which the data have already been analyzed, summarized and/or reformatted to fit the needs of the particular model. Application of habitat-based viability models may be more expensive than habitat models, because they require demographic data in addition to habitat data.

4 Recommendations Resulting From Model Review

1. Use Existing Habitat and Viability Models

In many cases, the currently available methods can be applied with no new model development, depending on the specific question asked, and on the ecology of the species involved. The model combination that provides the best capability to describe and evaluate habitat fragmentation issues at a landscape scale is a general habitat suitability model (e.g., using logistic regression) linked to a spatially explicit metapopulation-modeling program. As discussed in the previous section, only habitat-based viability models make predictions on the effects of fragmentation that are directly relevant to TES persistence in the landscape. Ramas GIS is the only one that can incorporate dynamic spatial structure and linkage ability to various GIS software; and the one with the most comprehensive technical support, though at a consultation fee cost.

There are both habitat and demographic models for many of the TES in military installations. Examples of demographic models for several species are given in (Breininger et al. 2000). Many of which have been implemented in Ramas GIS.

This combination of models (logistic regression for habitat modeling and Ramas GIS for demographic modeling) can be used to address both questions involving static landscapes (e.g., comparing “before” and “after” scenarios of fragmentation) or dynamic landscapes (in which the transitional landscapes are also modeled). Modeling dynamic landscapes requires predictions about the future of the landscape, which might be available from management plans or existing landscape models.

2. Develop Training Program

One of the most important factors preventing widespread and effective use of models in TES and land management issues is a lack of training. Many managers lack the experience to decide on appropriate kinds of models and scales of resolution that are best to solve a given problem (Breininger et al. 2000). Another important factor is the lack of appropriate and relevant data. This is often an extension of lack of

training, as managers who lack training in modeling do not know what types of data to collect to optimize the use of models. Table 30 lists some demographic models for species of interest in military installations.

Thus, teaching the use of existing models is the most efficient way to increase the use of models in land management issues. Teaching can take various forms, and can be done in a variety of formats. Both the content and the format of training should depend on the type of audience, such as managers and technical personnel.

Table 30. Examples of demographic models for species of interest in military installations.

Species	Reference
Species Critical To Army Installations	
Red-cockaded Woodpecker	Akçakaya Et Al. 1996; Cox & Engstrom 2001
Desert Tortoise	Doak Et Al. 1994; Root 1999
Golden-cheeked Warbler	Alldredge Et Al. 2004
Black-capped Vireo	U.S. F&Ws 1996
Other Priority TES In Military Installations	
San Joaquin Kit Fox	Cypher Et Al. 2000; Dunham Et Al. 2003
Sonoran Pronghorn Antelope	Hosack Et Al. 2002
Florida Scrub Jay	Root 1998
Southwestern Willow Flycatcher	U.S. F&Ws 2001
Marbled Murrelet	Akçakaya 1997
Hawaiian Hawk	Klavitter Et Al. 2003
Peregrine Falcon	Wootton & Bell 1992; Dunham Et Al. 2003
Northern Spotted Owl	Akçakaya And Raphael 1998
Mexican Spotted Owl	Seamans Et Al. 1999; Dunham Et Al. 2003
Least Tern	Akçakaya Et Al. 2003
Western Snowy Plover	Nur Et Al. 1999
Piping Plover	Ryan Et Al. 1993
Eastern Indigo Snake	Breininger Et Al. 2004
Loggerhead Sea Turtle	Crowder Et Al. 1994
Chinook Salmon	Ruckelshaus Et Al. 2004
Short-Nose Sturgeon	Root And Akçakaya 1997

3. Develop Software for Habitat Suitability Models

Although the habitat suitability models recommended here could easily be implemented in most statistical software packages (such as SAS and Statistica), there is a need for specialized software for estimating habitat suitability models based on habitat maps and occurrence data. Such a program would make it considerably easier to implement these models (without having to export the relevant data from GIS maps into data tables), and also to incorporate uncertainties, to run tests of validation, to visualize the results, and to export the resulting habitat model for use in vi-

ability models. Habitat suitability models have been integrated with PVA models to identify habitat patches and characterize the spatial structure of metapopulations (see species viability models, above).

4. Develop a Generic Landscape Prediction Model

The currently available landscape models either focus on human land use (with insufficient detail of natural land cover) or on natural vegetation dynamics (without incorporating human land use). Thus, there is a need for landscape model that includes both sufficient detail in vegetation classes (so as to be able to model habitat for TES) and explicit methods for predicting human land use change (such as urbanization). This model would predict the changes in land-use and land-cover based on human population growth and planned land management, as well as on ecological processes such as succession and disturbances. Another shortcoming of the most landscape models currently available is that they require substantial expertise to implement and to apply to specific cases. Thus, there is also a need to develop user-friendly programs.

5. Link Habitat-Landscape-Viability Models

To fully evaluate the impact of potential habitat fragmentation on TES, three types of models should be used together:

- Habitat Suitability Model
- Landscape Model (Natural And Land-Use)
- Viability Model.

These three types of models should be integrated in a single, user-friendly modeling platform. Such integration is conceptually very simple, and has been partially done. Ramas landscape, a program developed with funding from USDA, has integrated the landscape model landis and the viability model Ramas GIS. However, this model has two shortcomings: (1) it does not include a habitat model (although the user can enter a habitat model, the program does not estimate it), and (2) the landscape model does not include human land-use changes other than timber harvest.

To partially implement these recommendations, particularly the last, a study of the effects of landscape change on the Golden-cheeked Warbler in and near Fort Hood TX was conducted in 2004.

5 Application of the Golden-cheeked Warbler Habitat Fragmentation Model

Objective

The Golden-cheeked Warbler (*Dendroica Chrysoparia*) is an endangered neotropical migrant songbird with one of the most restricted breeding ranges in all of North America. Within the United States, it nests only in Texas. In 1990, the Golden-cheeked Warbler was placed on the Federal endangered species list due to declines in population, reductions of overall range, and continuing loss of nesting habitat (U.S. Fish and Wildlife Service 1990 1992).

The objective of this study is to demonstrate the use of habitat-based metapopulation modeling in evaluating the impact of habitat loss and fragmentation on the long-term persistence of the Golden-cheeked Warbler. Two very simple fragmentation scenarios are given here to demonstrate this approach.

Methods

A spatially explicit, stage-structured, stochastic model of the Golden-cheeked Warbler based on a habitat suitability map (diamond and true 1999) and a demographic model from Alldredge et al. (2004) was developed. The population viability analysis program Ramas GIS (Akçakaya 2002) was used to develop the model; Ramas GIS is designed to link landscape data from a geographic information system with a metapopulation model.

Data on the current distribution of the Golden-cheeked Warbler habitat was used to find the spatial structure of the metapopulation (i.e., to identify the location, size, and shape of habitat patches in which [sub]populations of the metapopulation exist). In addition to spatial structure, demographic parameters incorporated (e.g., carrying capacities, initial abundances and vital rates of each population, the amount of year-to-year viability in vital rates, as well as the rate of dispersal between and the degree of similarity of environmental fluctuations that different populations experience).

Stage Matrix

The demographic parameters in the model are based on a non-spatially explicit demographic model developed by Alldredge et al. (2004) using RAMAS Metapop. This model was run for males only because most of the information on Golden-cheeked Warblers is on males because they establish breeding territories. The model therefore assumes that males are monogamous and that sex ratios of offspring are 1:1. It also assumes that the dynamics of females are similar to males and that territorial males will mate and produce offspring.

The model used two age classes, hatch year (HY) and after-hatch year (AHY), and assumed a post-breeding census. The matrix estimated HY fecundity as the product of survival and fledging rate for each stage and estimated its variance using Equation 5 of Goodman (1960). Estimates of fledging rate and survival were obtained from several studies conducted at the Department of Defense's Fort Hood military base (U.S. Fish and Wildlife Service 1996, Anders 2000) and other sources (see U.S. Fish and Wildlife Service 1996).

Uncertainty in vital rates was incorporated by using three estimates of fecundity and survival: low, intermediate, and high (Table 31). The highest and lowest documented rates were used for the high and low parameter estimates. Intermediate rates fell between these two estimates.

Table 31. Parameters used in the stage matrix.

	Fecundity		Survival	
	HY	AHY	HY	AHY
High	0.72	0.94	0.5	0.57
Intermediate	0.48	0.74	0.4	0.57

Habitat Suitability Map

The habitat map was developed by classification of Thematic Mapper (TM) satellite imagery by Diamond and True (1999). Areas classified as 'Ashe juniper or mixed Ashe juniper-oak forest', 'Ashe juniper, mixed, or mainly deciduous forest', or 'Ashe juniper or mixed Ashe juniper-oak woodland' were identified as Golden-cheeked Warbler habitat. Additionally, cells were considered habitat only if they occurred within 1 km of a 5 ha or larger habitat patch (Figure 14). This raster (grid) map consisted of 11,634 columns and 10,599 rows. Each cell was 28.5 m x 28.5 m (812.25 m2) and had a value of 0 (non-habitat) or 1 (habitat). There were 4,887,965 cells (~139 km2) with a value of 1. This map was constructed by aggregating the pixels in a region of 8 by 8 cells into one. The resulting map had a 228 m resolution and

habitat suitability values ranging from zero for non-habitat to one for optimal habitat.

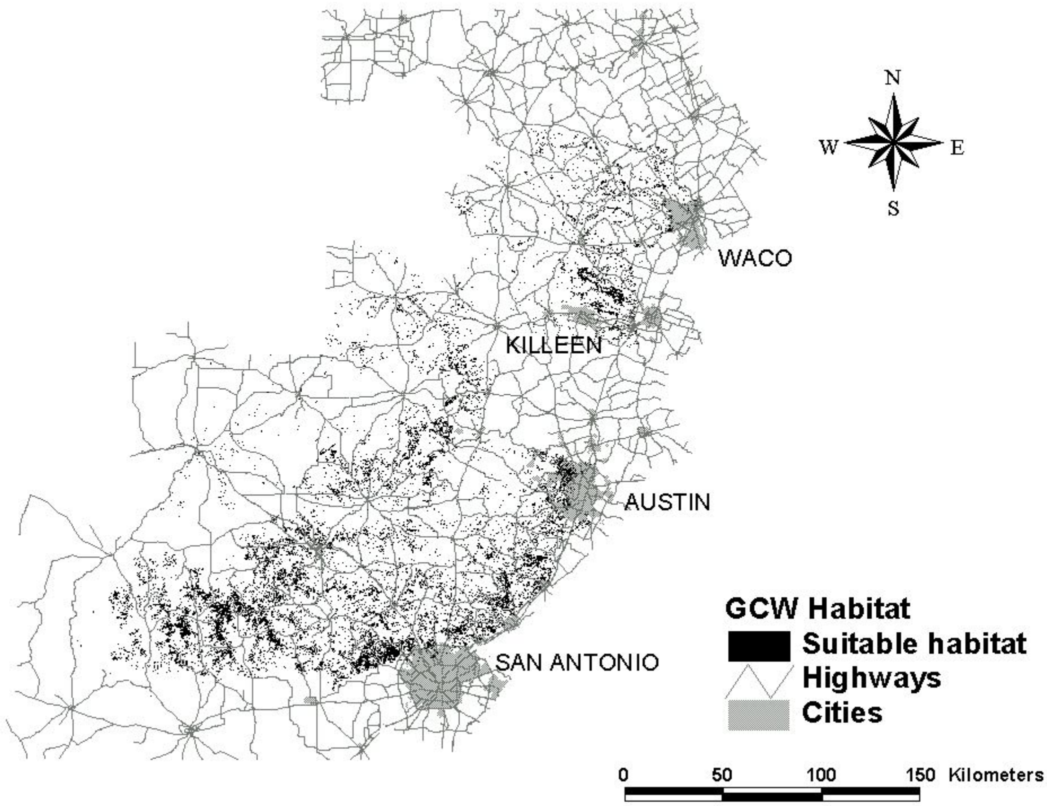


Figure 14. Suitable habitat for Golden-cheeked Warblers during the summer breeding season in Texas.

The habitat map is linked to the metapopulation model through two parameters: threshold habitat suitability (HS) and neighborhood distance. Threshold HS is the minimum habitat suitability value below which the habitat is not suitable for survival and/or reproduction. The threshold HS used here was 0.1 (10 percent); cells with a habitat value of 0.1 or less were not considered when habitat patches were analyzed.

Neighborhood distance is used to identify nearby cells that belong to the same patch and represents the spatial scale at which the population can be assumed to panmictic. Suitable cells (i.e., those with a habitat value above the threshold habitat suitability) separated by a distance less than or equal to the neighborhood distance are regarded to be in the same patch. A neighborhood distance of 8.77 cells was used, which corresponds to the assumption that any two suitable locations within about 2

km of each other are considered to be in the same patch. The population was assumed to be panmictic at this spatial scale based on the average dispersal distance of juvenile males (4.04 km ± 4.78 SD).

Carrying Capacity and Initial Abundances

Carrying capacity (K) was estimated based on the average territory size of 6.7 ha. The number of territories per cell (5.2 ha cell size/6.7 ha = 0.776) was used as a scaling constant in calculating the carrying capacity of each patch by multiplying it with the total habitat suitability of each patch. Patches with a carrying capacity of less than 10 individuals were excluded. This calculation resulted in a total carrying capacity of 47,246, well above the 4,800-16,000 pairs estimated for the breeding range. Thus a second estimate of K was used by adjusting the scaling constant to 0.27, which resulted in a total carrying capacity of 16,395. For both models, the initial abundance in each patch was one-half the carrying capacity and distributed between the HY and AHY stage classes according to the stable age distribution of the model.

Density Dependence

Density dependence was modeled using the ceiling model with the carrying capacities based on habitat data as population ceilings. Under this type of density dependence, the population fluctuates independently of population size, according to the stage matrix and standard deviation matrix, until it reaches the ceiling. The population remains at this level until a population decline takes it below the ceiling.

Dispersal

In the model described here, dispersal refers to the movement of birds among habitat patches. The dispersal rate (proportion dispersing from target to source population) may depend on the distance between the source and target populations and the stage of the individual. Adults show strong site fidelity, thus the dispersal rate in adults was assumed to be negligible and dispersal was only modeled for HY males.

Dispersal among HY males occurred according to the function:

$$m_{ij}=\exp(-D_{ij}/b)$$

where:
D is the distance between two populations
b is the average dispersal distance
m is the dispersal rate.

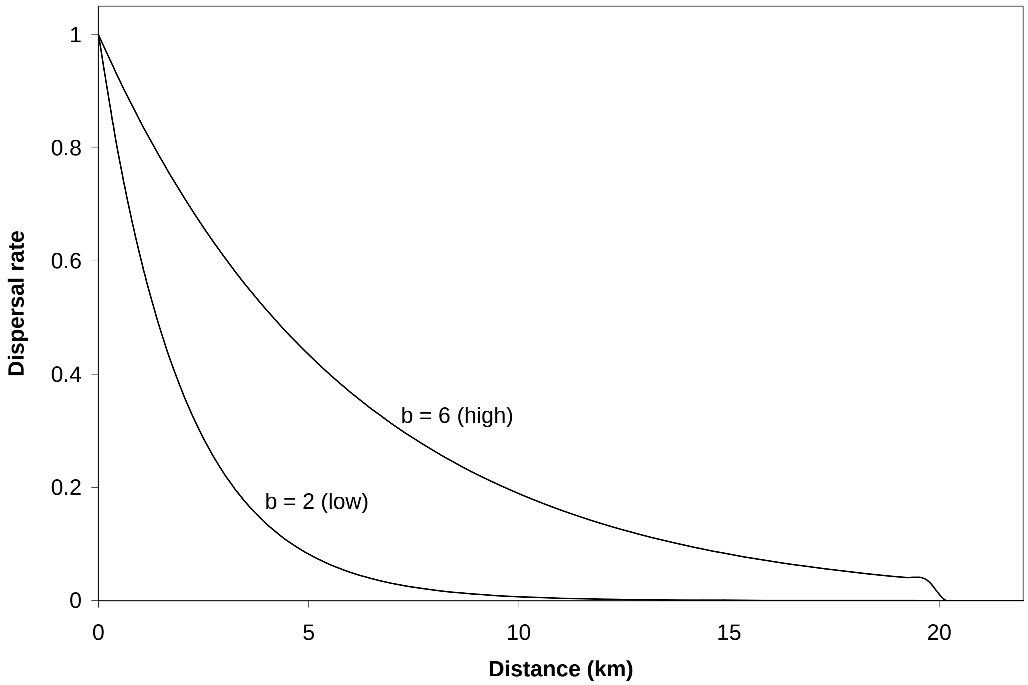


Figure 15. Dispersal rate of hatch-year males as a function of distance. The curves are the function y = exp(-x/b).

In addition, the above equation was modified to reflect a maximum dispersal distance of 20 km. Dispersal was modeled at two levels by setting the average dispersal distance (b) to 2.0 and 6.0 km for low and high dispersal (Figure 15). The distance metric used in the model is the distance between the centers of the patches.

Correlation-distance Function

A correlation in the vital rates among populations may increase the overall variability of the total abundance and decrease the viability of the metapopulation. In this model, two different correlation-distance functions were used to set the correlation of vital rates among populations. The function used was:

$$C = exp(-d/b)$$

where

C is the coefficient of correlation between the vital rates of two populations

d is the distance between the centers of these two populations

b is a parameter that describes the rate at which the correlation declines with increased distance between populations (b values of 500 and 100 were used here for high and low correlation.) (Figure 16)

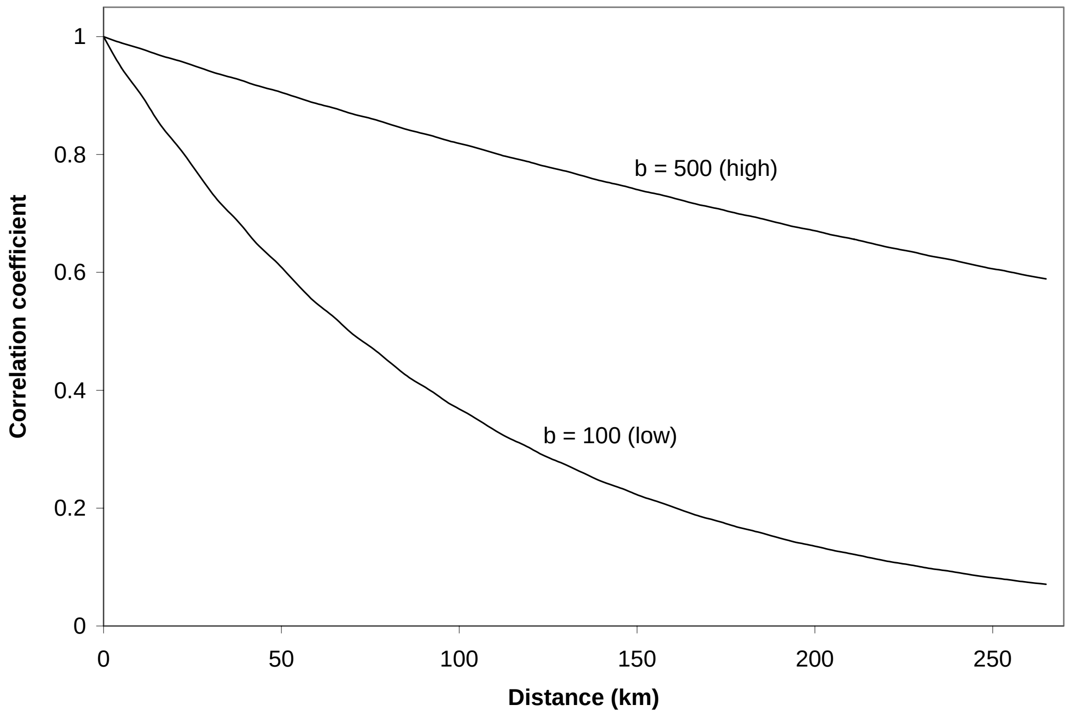


Figure 16. Correlation-distance functions used in the model. The curves are the function y = exp (-x/b), which gives the correlation in vital rates of two populations separated by a given distance.

Fragmentation Scenarios

Habitat fragmentation was modeled by reducing the amount of available habitat every 5 years for a period of 50 years. Two scenarios of habitat loss, low and high, were modeled to compare the effects of different levels of habitat encroachment. Future habitat loss is difficult to predict, however areas currently developed were assumed likely to experience further expansion. Therefore, fragmentation was modeled as a function of the distance of the habitat from cities and highways.

A habitat suitability function was created that links habitat characteristics to a measure of habitat suitability. For this model, the proximity of a cell to the nearest city and highway was used as a habitat characteristic that influences suitability. Habitat within a specified distance, X meters, from a city or within a distance of 2X from a city and within 1 km of a highway was considered unsuitable (i.e., habitat value = 0). To model temporal changes in habitat, a time series of habitat maps was created where the distance X was increased every 5 years. For low habitat loss, the distance X was increased in 150 m increments from 0 to 1,500 m. In high habitat loss models, X was increased in 1,000 m increments from 0 to 10,000 m (Figure 17). Simulations were also run without habitat loss and the results were compared.

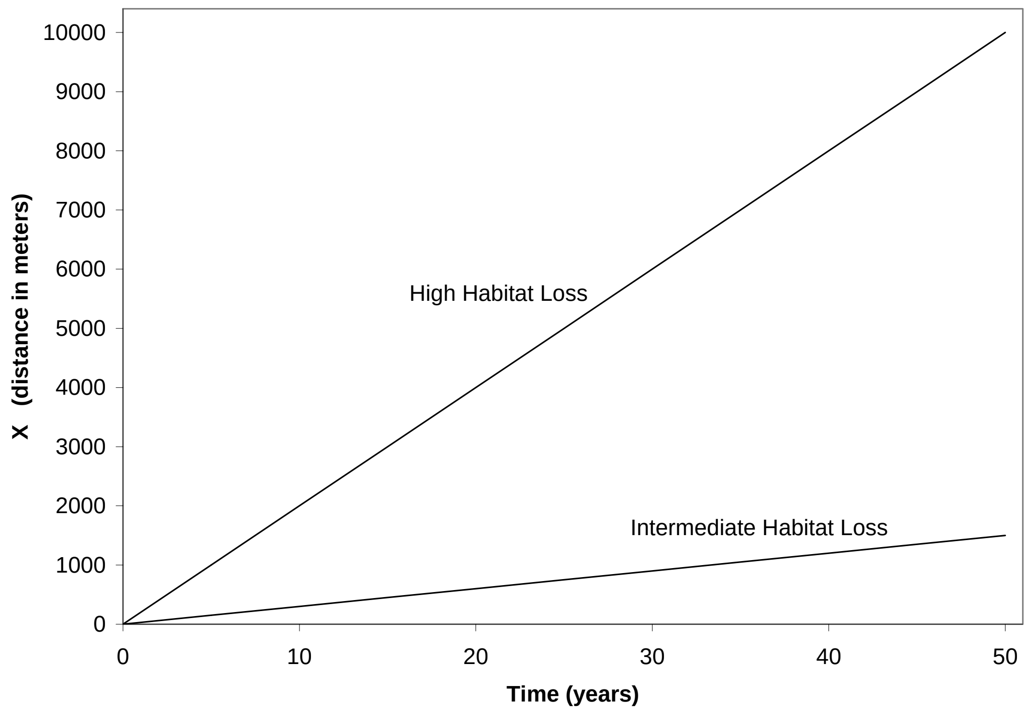


Figure 17. Habitat loss functions used in the model. Habitat within a distance, X, from a city or within 2X from a city and 1,000 meters of a highway was considered unsuitable habitat. "X" was increased every 5 years for 50 years.

It was assumed that habitat loss and fragmentation were affected only available habitat, which was reflected in the number, location, and carrying capacities of the habitat patches. The location of habitat patches determine their distances to neighboring patches, thus affecting dispersal rates. Other aspects of the species demography (in particular survival rates and fecundities) were assumed to be unaffected by habitat loss and fragmentation. The "Discussion" chapter (p 105) returns to this issue.

Analysis and Viability Measures Used

The analysis of the dynamics of the Golden-cheeked Warbler metapopulation consisted of a series of simulations. Each simulation consisted of 1,000 replications, and each replication projected the abundance of each population for 50 years.

To analyze the sensitivity of the model results to parameters, three simulations were run for each parameter, using the lower, intermediate, and upper estimates of that parameter and medium estimates of all other parameters. Two measures Were used to express the predicted viability of the metapopulation: (1) risk of 85 percent

decline in metapopulation abundance and (2) risk of falling below the metapopulation threshold of 5,000 birds anytime within 50 years.

Results

Patch Structure

Nineteen patches were found in the simulations based on an average territory size of 6.7 ha. Total carrying capacity was 47,246. Using a lower estimation of K resulted in delineation of 10 patches and a total carrying capacity of 16,395. In both models, the largest patch made up about 75 percent of the total area of all patches and the two largest patches together made up about 98 percent.

Carrying Capacity

The results of simulations with different carrying capacities produced similar results. There was no significant difference in percent decline between the low and high carrying capacity models. In absolute numbers, the low K models declined to a smaller population size than in the high K models due to the smaller initial population size in the low K models.

Dispersal

The major effect of dispersal was on metapopulation occupancy. Using medium values for all other parameters, at the end of the 50-year simulations 5.4 ± 2.1 (mean ± s.d.) populations were occupied in the low dispersal model and 6.4 ± 2.5 were occupied in the high dispersal model. The population trajectory and extinction risk did not significantly differ between the low and high dispersal models (Kolmogorov-Smirnov test; $D = 0.033$, $p = 0.65$).

Correlation

The correlation among vital rates of populations had a more pronounced effect on the risk of decline. Under the assumption of medium values for all other parameters, the risk of 85 percent decline was 0.1540 and 0.2130 for low and high correlation, respectively. The risk of declining below a population abundance of 13,000 was greater in the high correlation model than the low correlation model (Figure 18). However, the risk of decline to an abundance between about 13,000-30,000 was greater in low compared to high correlation models. The risk curves for low and high correlation models were significantly different (Kolmogorov-Smirnov test; $D = 0.082$, 7$p = 0.0024$).

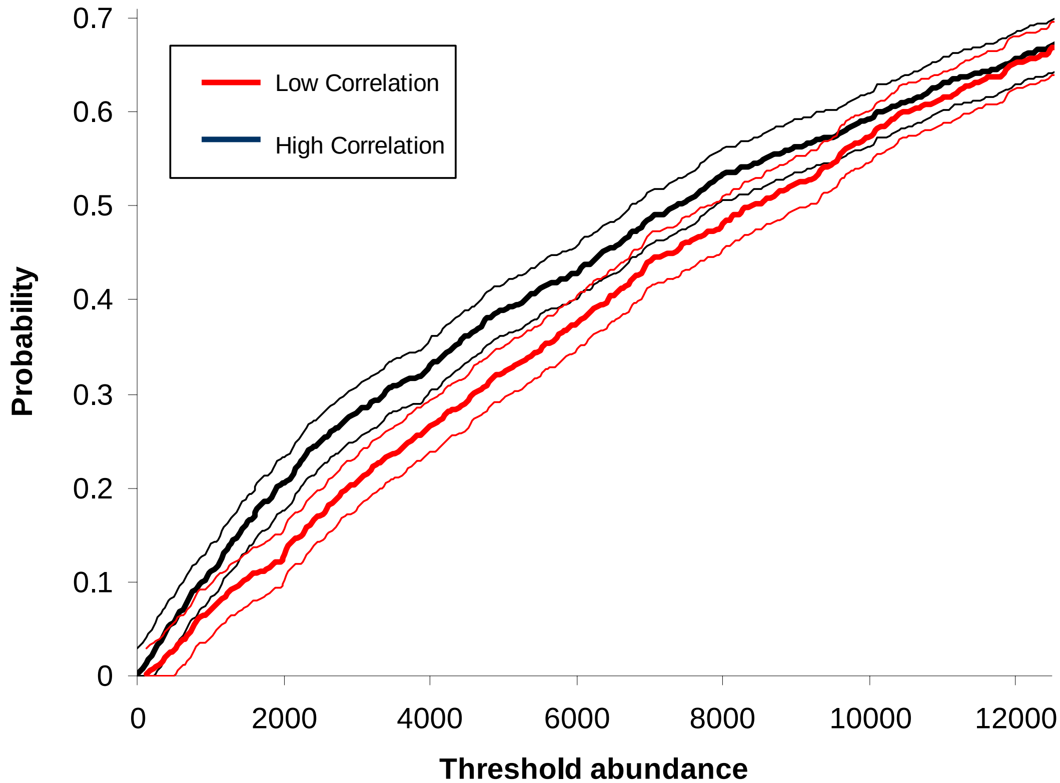


Figure 18. Effect of correlation coefficient on extinction risk. The curves show the probability of falling below a threshold abundance in 50 years.

Habitat Fragmentation

The habitat fragmentation scenarios resulted in a reduction in the amount of available habitat (Figure 19). In low habitat loss, about 8.6 percent of the habitat area was lost, and in high habitat loss about 48 percent was lost. Using medium values of carrying capacity, dispersal, and correlation parameters, the mean abundance after 50 years was 10,724 for no habitat loss, 9,897 for low, and 5,355 for high habitat loss. The habitat loss that occurred also resulted in a greater number of populations, with a mean metapopulation occupancy at the end of the 50-year simulations of 6.2 for no habitat loss, 8.1 for low, and 48.8 for high habitat loss.

The fragmentation of habitat resulted in a greater risk of decline. The probability of metapopulation abundance declining by 85 percent within 50 years was 0.1850, 0.2010, and 0.3190 for no, low, and high habitat loss respectively.

The carrying capacity used in the model affected the percent decline in abundance for some models. For no habitat loss and low habitat loss, the percent decline did not significantly differ between low and high carrying capacity models. There was a

significant difference in percent decline between the low and high K models for the high dispersal models with high habitat loss (Table 32). Percent decline was similar for no habitat loss and low habitat loss and higher in high habitat loss models (Figure 20; Table 31).

The risk of decline of the species to 5,000 birds within the next 50 years was different under different carrying capacities and dispersal and correlation functions (Table 33). The low carrying capacity models had a higher risk than the high carrying capacity models. For low carrying capacity models, risk of decline was greatest in high habitat loss scenarios and the range in the risk of decline was similar for no and low habitat loss scenarios. Under no habitat loss, the low correlation models had a lower risk than high correlation models.

In the high carrying capacity models, the risk of declining to less than 5,000 birds ranged from 0.4330 to 0.5660 for no loss, 0.4540 to 0.5750 for low loss, and 0.5010 to 0.7570 for high habitat loss. In all three habitat loss scenarios, the lowest risk occurred with low dispersal and low correlation parameters. Under the two fragmentation scenarios, the high dispersal and high correlation parameters resulted in the greatest risk.

The results showed sensitivity to the estimates of fecundity and survival. Risk of decline to 5,000 birds in 50 years ranged from 0.9970 to 0.0790 for low and high HY fecundity estimates (Figure 21) and from 0.9200 to 0.2370 for low and high AHY fecundity. Risk ranged from 0.9860 to 0.1900 for HY survival (Figure 22). The results were not sensitive to density-dependent dispersal.

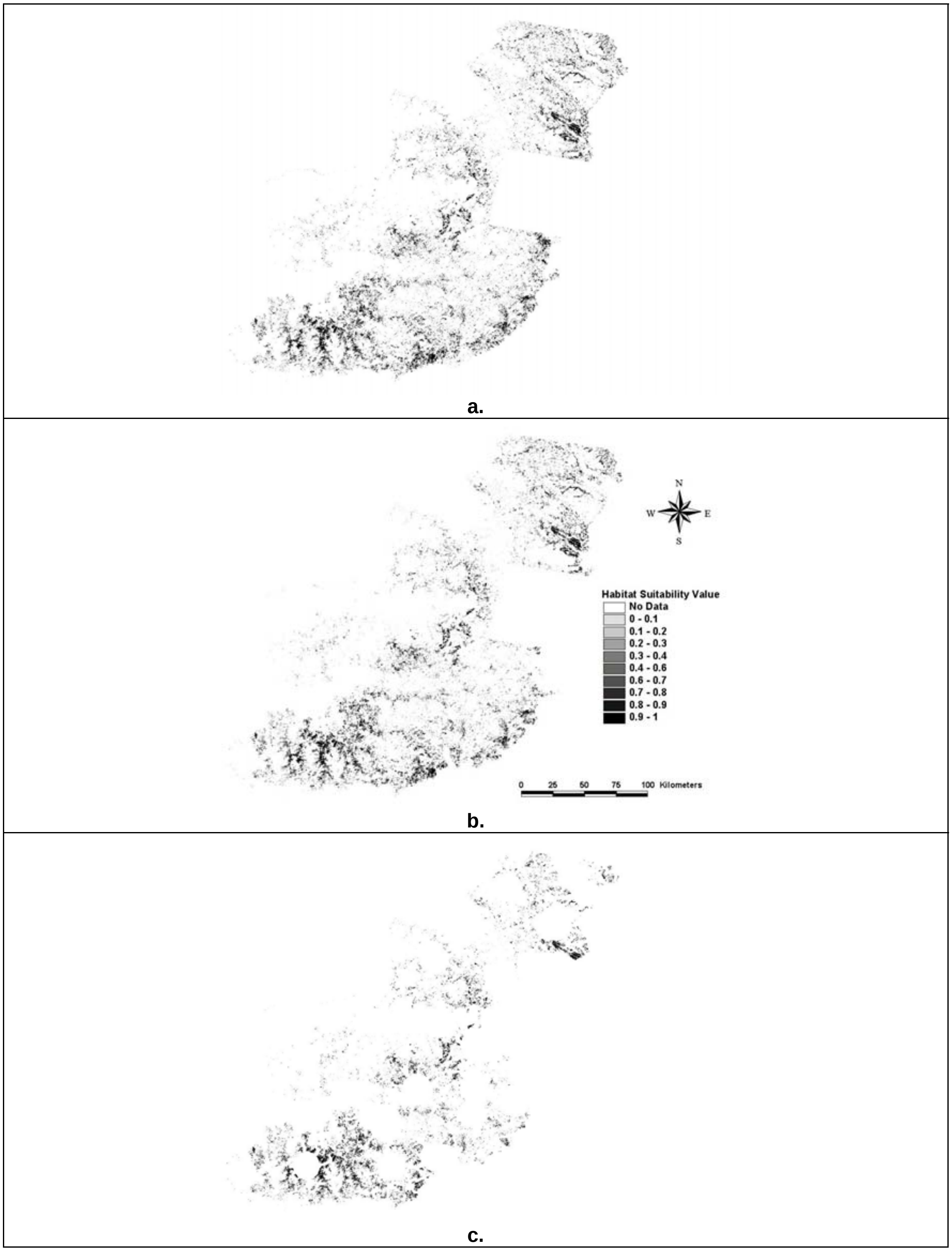


Figure 19. Distribution of Golden-cheeked Warbler habitat after 50 years under fragmentation scenarios of (a) no habitat loss, (b) low habitat loss, and (c) high habitat loss.

Table 32. Probability of 85% decline in metapopulation abundance in 50 years for high carrying capacity models. Numbers in parentheses are 95% confidence intervals. Results of low K models were similar, except in high dispersal models and high habitat loss.

		Habitat Loss		
		None	**Low**	**High**
Low Dispersal	Low Correlation	0.1500	0.1370	0.1940
		(0.1220, 0.1780)	(0.1090, 0.1650)	(0.1660, 0.2220)
Low Dispersal	High Correlation	0.2240	0.2310	0.2740
		(0.1960, 0.2520)	(0.2030, 0.2590)	(0.2460, 0.3020)
High Dispersal	Low Correlation	0.1520	0.1570	0.3670[a]
		(0.1240, 0.1800)	(0.1290, 0.1850)	(0.3390, 0.3950)
High Dispersal	High Correlation	0.2310	0.2180	0.4320[b]
		(0.2030, 0.2590)	(0.1900, 0.2460)	(0.4040, 0.4600)
a Low K model probability = 0.2940 (Kolmogorov-Smirnov test; D = 0.080, p = 0.0033)				
b Low K model probability = 0.3780 (Kolmogorov-Smirnov test; D = 0.068, p =0.0196)				

Table 33. Probability of decline to 5,000 birds in 50 years. Numbers in parentheses are 95% confidence intervals.

			Habitat Loss		
High Carrying Capacity			**None**	**Low**	**High**
	Low Dispersal	Low Correlation	0.4330	0.4540	0.5010
			(0.4050, 0.4610)	(0.4260, 0.4820)	(0.4730, 0.5290)
	Low Dispersal	High Correlation	0.5660	0.5470	0.6280
			(0.5380, 0.5940)	(0.5190, 0.5750)	(0.6000, 0.6560)
	High Dispersal	Low Correlation	0.4530	0.4580	0.7120
			(0.4250, 0.4810)	(0.4300, 0.4860)	(0.6840, 0.7400)
	High Dispersal	High Correlation	0.5330	0.5750	0.7570
			(0.5050, 0.5610)	(0.5470, 0.6030)	(0.7290, 0.7850)
Low Carrying Capacity					
	Low Dispersal	Low Correlation	0.9420	0.9420	0.9850
			(0.9140, 0.9700)	(0.9140, 0.9700)	(0.9570, 1.0000)
	Low Dispersal	High Correlation	0.9440	0.9560	0.9900
			(0.9160, 0.9720)	(0.9280, 0.9840)	(0.9620, 1.0000)
	High Dispersal	Low Correlation	0.9350	0.9460	0.9980
			(0.9070, 0.9630)	(0.9180, 0.9740)	(0.9700, 1.0000)
	High Dispersal	High Correlation	0.9590	0.9390	0.9940
			(0.9310, 0.9870)	(0.9110, 0.9670)	(0.9660, 1.0000)

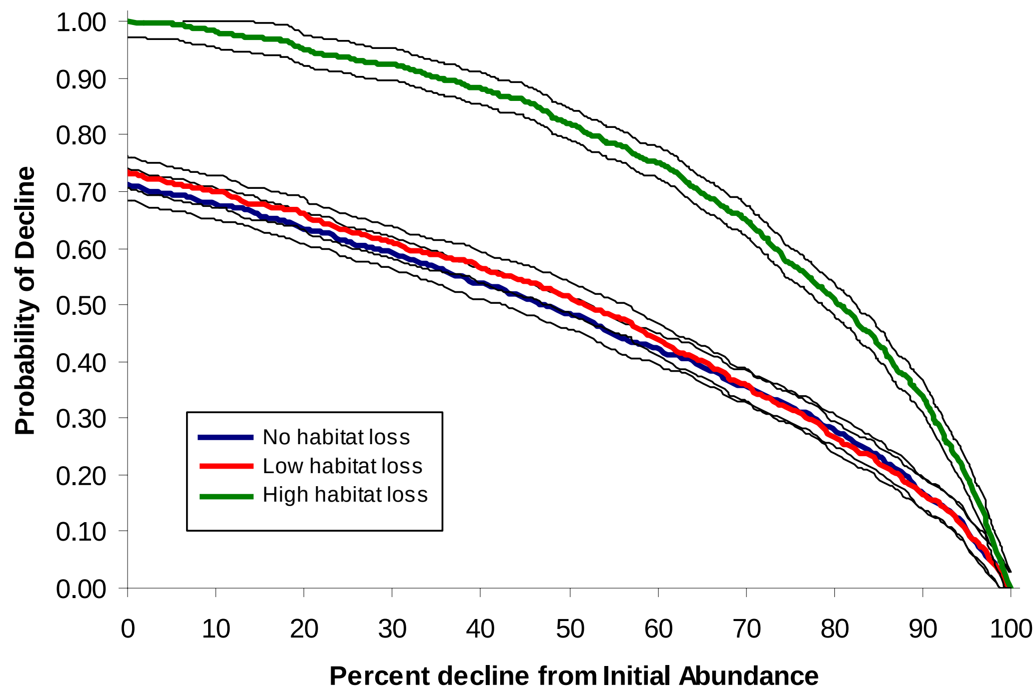


Figure 20. Terminal percent decline under different habitat loss scenarios for the high carrying capacity, high dispersal, and high correlation model. The curves represent the probability of metapopulation abundance declining by a given percent in 50 years.

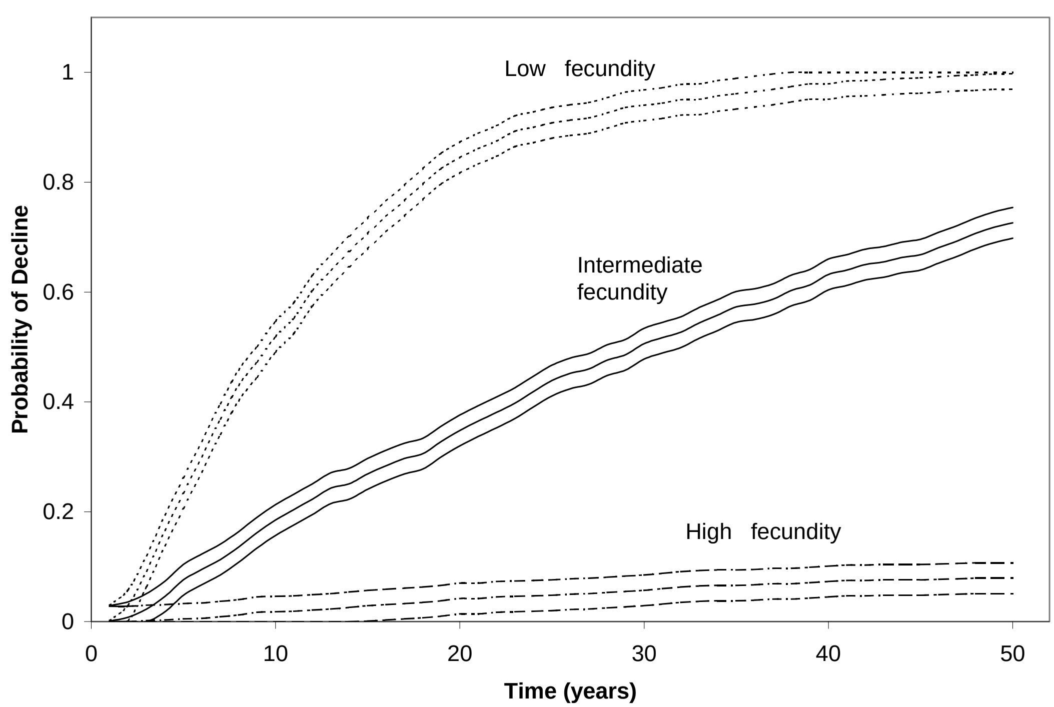


Figure 21. Sensitivity of risk of decline to hatch year fecundity. The curves represent the probability of declining to 5,000 birds in 50 years.

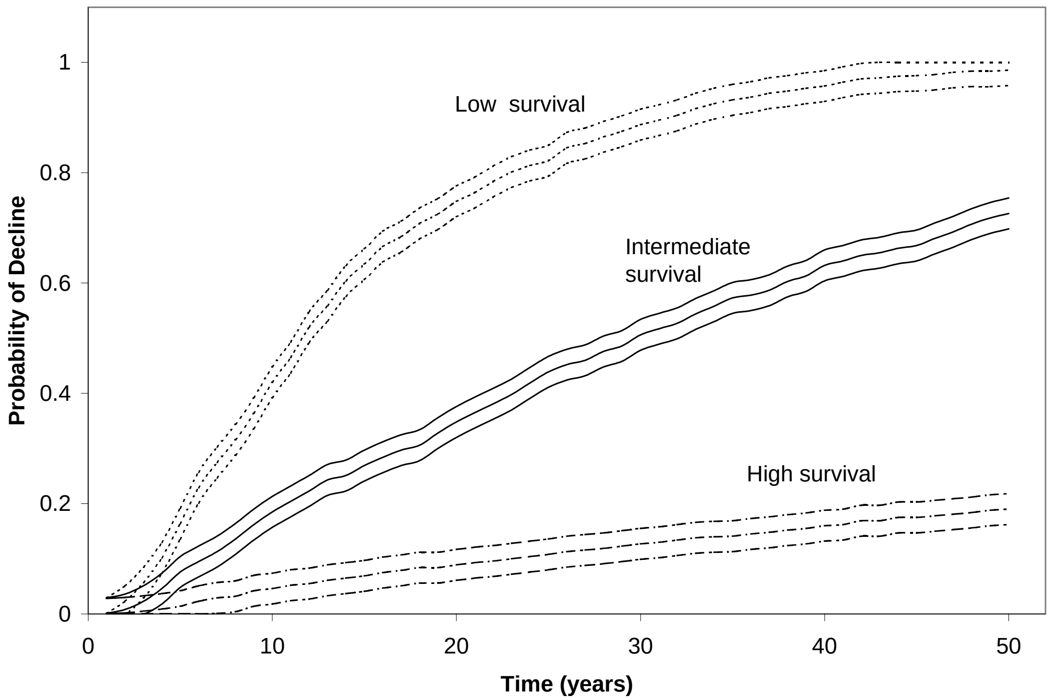


Figure 22. Sensitivity of risk of decline to hatch year survival.

6 Discussion

The spatial structure derived depends on the accuracy of the habitat map. The habitat map used is based on vegetation classification from TM satellite imagery, with no verification conducted on the ground. The actual occurrence of Golden-cheeked Warblers in areas classified as habitat or non-habitat is therefore unknown. Areas may have been misclassified due to the nature of TM imagery, the inability to recognize habitat variables such as tree age, and difficultly distinguishing between woodland and savanna. Due to these limitations, the classification of land cover into 'habitat' and 'non-habitat' is believed to be about 80 percent accurate (Diamond and True 1999). The accuracy of the map will influence the habitat suitability function, recognition of patches, carrying capacity, and initial abundance.

The selected fragmentation scenarios were based only on the distance from roads and cities. Future fragmentation is difficult to predict, as it undoubtedly depends on many other factors, including social and economic ones. Thus, future fragmentation assessments like this study must be considered only as "what if" projections, rather than forecasts of future conditions.

An important aspect of evaluating the impact of habitat loss and fragmentation is determining the model parameters that will be affected. In this study, habitat loss and fragmentation affected several model parameters, including distances among populations (which determine dispersal rates and spatial correlations), number of populations, and carrying capacities of populations. Other aspects of the species demography (in particular survival rates and fecundities) were assumed to be unaffected by habitat loss and fragmentation. This may not be a valid assumption. Increased fragmentation may cause increase edge effects (because each habitat patch is smaller, and thus a larger proportion of each habitat patch is closer to an edge between the habitat patch and the surrounding landscape). Edge effects may result in lower survival and fecundity. Such effects can only be documented through comparative field studies that allow multi-annual estimation of survival and fecundity in habitat patches of different sizes. In the absence of such data, it was assumed that these effects did not exist. Despite this optimistic assumption, the results indicate that loss of habitat around existing roads and cities may cause substantial decrease in long-term viability of this species.

In the simulations done here, the viability of the metapopulation was influenced by both landscape dynamics and demographic variables. Habitat loss affected the total

habitat area, the number of occupied patches, mean metapopulation abundance, and the viability of the species.

The sensitivity analysis conducted gives information about which parameters need to be estimated more carefully. The results were extremely sensitive to both survival and fecundity estimates. High vital rates were estimated from Fort Hood, where active management strategies are in place. This estimate may therefore be overly optimistic for the entire habitat range. Improved estimates of vital rates and their association with habitat quality would greatly improve future models and therefore management decisions.

The sensitivity of the results of this work suggests the results should not be interpreted in absolute terms. The model serves as a way to compare possible fragmentation and management scenarios and not as a way to predict future abundance in absolute numbers. Results from sets of possible scenarios can be compared in relative terms to evaluate management options.

Despite the high sensitivity of the results to some parameters, the predicted effect of habitat loss was robust to uncertainties in the model. Under any combination of uncertain model parameters (such as vital rates, dispersal or correlation functions), low habitat loss resulted in higher viability than high habitat loss. For example, under both low and high dispersal rates, the high habitat loss results in higher risks. Thus, even if the precise value of some model parameters were unknown, habitat fragmentation scenarios can still be compared or ranked with respect to their effect on the viability of the Golden-cheeked Warbler.

The implicit assumption in this assessment of model robustness is that these factors (such as dispersal or correlation functions) will not change substantially under habitat loss and fragmentation. There is no reason to think that they will change, and this assumption does not preclude changes in the values of dispersal or correlation between any two particular populations, or the total number of dispersers in the metapopulation, or the average correlation in the metapopulation. These particulars will change depending on the number and configuration of populations (which of course is affected by fragmentation); the assumption only involves the functions (dispersal-distance and correlation-distance functions).

The model results (the effect of habitat loss) are also robust with respect to vital rates, despite the fact that fragmentation may affect average vital rates (because of edge effects). The reason is that any expected affect of fragmentation on vital rates will more likely increase the difference between low and high habitat loss than decrease the difference.

7 Conclusions and Recommendations

This work has reviewed, tested, and evaluated six habitat fragmentation models as they relate to military installations within the United States: FragStats, Patch Analyst, HAMS, HSI, RAMAS GIS, and EAM. An in-depth investigation was also performed of one application at Fort Hood, TX.

This study has demonstrated how to consider both demographic and landscape dynamics in assessing impacts and evaluating management decisions for the Golden-cheeked Warbler. Considering only demography or only landscape changes may be misleading, because the viability of the species depends on both demographic and landscape variables. Successful assessment of management options must include both demography and landscape dynamics.

This document also provides installation land managers with an initial source reference document on habitat fragmentation issues of concern to Army Military Installation Land Managers, and approaches to identifying appropriate land for protection under the Army Compatible Use Buffer (ACUB) program.

Based on the results of sensitivity analysis and the predicted impact of habitat loss, this work recommends that future studies focus on the following aspects of the Golden-cheeked Warbler ecology and landscape dynamics:

- Updating the existing habitat map by developing and validating a quantitative habitat suitability model, using up-to-date land-use and land-cover information
- Estimating multi-annual survival and fecundity in habitat patches of different size and different habitat quality, based on the updated habitat map
- Estimating the total current population size and structure by a stratified sampling based on the update habitat map
- Developing realistic landscape change scenarios based on past changes in land-use and current human population trends in the area.

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Appendix: Fragstats Metrics

Metric Class	Metric	Symbol	Units	Description
Area	Patch area	AREA	hectares(ha)	area of patch
	Patch perimeter	PERIM	meters(m)	perimeter of patch, including internal holes, regardless of whether perimeter represents true edge or not (ie. landscape boundary)
	Radius of gyration	GYRATE	meters(m)	mean distance (m) between each cell in patch and patch centroid
	Total area	CA/TA	hectares(ha)	total area (of class, landscape)
	Percentage of landscape	PLAND	percent(%)	percentage of class in landscape
	Number of patches	NP		count of the total number of patches (of class or landscape)
	Patch density	PD	# per 100 ha	(# patches of a type/TA) x 10,000 x 100 --this expresses NP on a per unit area basis that facilitates comparisons among landscapes of varying size
	Largest patch index	LPI	percent(%)	% of landscape that is taken up by the largest patch
	Landscape shape index	LSI		simple measure of class aggregation/clumpiness, >1
	Normalized LSI	nLSI		0<nLSI<1, =0 when landscape single square patch of corresponding type, =1 when patch type maximally disaggregated, the normalization rescales LSI to min & max values possible for any class area
	Total edge	TE	meters(m)	absolute measure of total edge length of a patch type
	Edge density	ED	m/ha	sum of lengths of all edge segments of a patch type divided by total landscape area and converted to ha, >0, =0 when no class edge in landscape
Shape	Shape index	SHAPE		index =1 when perfect square, increases with complexity
	Perimeter-Area ratio	PARA		ratio of patch perimeter to area, it is affected by cell size (as increases, PARA decreases)
	Fractal dimension index	FRAC		reflects shape complexity across range of patch sizes, overcoming limitations of PARA as a measure of shape complexity1<FRAC<2, =1 with simple perimeter, =2 with convoluted, plane filling perimeter
	Perimeter-area fractal dimension	PAFRAC		similar to FRAC, but on a class scale; useful for large sample sizes (n>20), values range 1-2
	Linearity index	LINEAR		based on medial axis transformation, =0 for square patches and =1 for patches which are all edge
	Related circumscribing circle	CIRCLE		provides a measure of overall patch elongation, ranges 0 (circle) - 1 (elongated)

Metric Class	Metric	Symbol	Units	Description
	Contiguity index	CONTIG		0<CONTIG<1, 0= 1pixel patch, increases to 1 as patch connectedness increases, its an index of patch boundary and thus shape
Core	Core area	CORE	hectares(ha)	area within the patch that is further than the specified depth-of-edge distance from patch perimeter
	Number of core areas	NCA		
	Core area index	CAI	percent(%)	relative index that quantifies core area as a percentage of patch area (ie. the percentage of the patch that is core area)
	Average depth index	ADEPTH	meters(m)	represents the average depth to the core of the patch, sensitive to both patch size and shape
	Maximum depth index	MDEPTH	meters(m)	describes the most compact and widest part of the patch, sensitive to both patch size and shape
	Total core area	TCA	hectares(ha)	same as CORE, but aggregated over all patches of corresponding type
	Core area percentage of landscape	CPLAND	percent(%)	same as CORE, but computed as a percentage of total landscape area
	Disjunct core area density	DCAD	# per 100 ha	expresses number of disjunct core area on a per unit area basis, to facilitate comparisons among landscapes of varying size
Isolation/ Proximity	Proximity index	PROX		represents the consideration of size and proximity of all patches whose edges area within a specified search radius of the focal patch, index =0 if patch has no neighbors of same patch type within the search radius, upper limit of index is affected by search radius and min.distance between patches
	Similarity index	SIMI		modification of PROX, SIMI considers size and proximity of all patches, regardless of class, whose edges are within a specified search radius of the focal patch
	Euclidean nearest neighbor distance	ENN	meters(m)	shortest straight-line distance between focal patch and nearest neighbor of same class, approaches 0 as distance decreases
	Functional nearest neighbor distance	FNN	meters(m)	accounts for fact that shortest geographic distance may not be shortest ecological distance perceived by organism/process, approaches 0 as distance to neighbor decreases
Contrast	Edge contrast index	ECON	percent(%)	relative measure of the amount of contrast along the patch perimeter (contrast specified by user)
	Contrast-weighted edge density	CWED	m/ha	standardizes edge to a per unit area basis that facilitates comparison among landscapes of varying sizes

Metric Class	Metric	Symbol	Units	Description
	Total edge contrast index	TECI	percent(%)	similar to ECON, but applied to all edges of corresponding patch type
Contagion	Percentage of like adjacenies	PLADJ	percent(%)	calculated from adjacency matrix, shows frequency with which different paris of patch types (including adjacencies between same patch type) appear side-by-side on map
	Clumpiness index	CLUMPY		index -1=max. disaggregated, 0=random, 1=max. aggregated
	Agreggation index	AI	percent(%)	calculated from adjacency matrix, shows frequency with which different paris of patch types (including adjacencies between same patch type) appear side-by-side on map; AI takes into account only like adjacencies involving focal class, not other patch types
	Interspersion & Juxtaposition index	IJI	percent(%)	isolates the interspersion or intermixing of patch types, not a measure of class aggregation, 0 (adjacent to only 1 patch type) < IJI < 1 (adjacent to all other patch types)
	Landscape division index	DIVISION	proportion	based on cumulative patch area distribution, interpreted as probability that two randomly chosen pixels in landsacpe are not situated on the same patch or corresponding patch type
	Splitting index	SPLIT		effective mesh number, or # patches with a constant patch size when corresponding patch type is subdivided into S patches, where S is value of splitting index 1 (all cells differ) < SPLIT < #cells^2 (single patch)
	Contagion	CONTAG	percent(%)	inversely related to ED, affected by both dispersion and intersperin of patch types
Connectivity	Cohesion	COHESION		measure the physical connectedness of corresponding patch type, values 0-100
	Connectedness index	CONNECT	percent(%)	defined on the # functional joinings between patches of a type, where each pair of patches is either connected or not based on a user-specified distance criterion, reported as percentage of maximum possible connectance given NP
Diversity	Patch richness	PR		# different patch types
	Patch richness density	PRD	# per 100 ha	standardizes PR to area for comparison among multiple landscapes
	Relative patch richness	RPR	percent(%)	represents patch richness as percentage of maximum potenial richness as specified by user
	Shannon's diversity index	SHDI		>0, 0 (1 patch), increases as more patch types and/or proportional area becomes equitable

Metric Class	Metric	Symbol	Units	Description
	Simpon's diversity index	SIDI		value of index represents the probability that any 2 pixels selectged at random would be different patch types, less sensitive to presense of rare types
	Modified Simpson's diversity index	MSIDI		transforms SIDI into one that belongs to general class of indices to which SHDI belongs
	Shannon's even-ness index	SHEI		0 (1 patch, approaches 0 as 1 patch dominates) < SHEI < 1 (even distribution of patch types)
	Simpon's evenness index	SIEI		expressed such that even distribution of area among patch types results in maximum evenness (1)
	Modified Simpson's evenness index	MSIEI		expressed such that an even distribution of area among patch types results in maximum evenness (same as above)
		Metric Sub-units	Subunit	Description
			MN	mean
			AM	area weighted mean
			MD	median
			RA	range
			SD	standard deviation
			CV	coefficient of variation
			CSD	# standard deviations from class mean
			CPS	percentile of class distribution (0= lowest metric, 100=highest metric)
			LSD	# standard deviations from landscape mean
			LPS	percentile of landscape distribution

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14. ABSTRACT

Although Army lands must primarily support troop training, the Army is also required to manage its training lands to meet other objectives, e.g., maintaining threatened and endangered species (TES) habitat. Because military training is more compatible with TES habitats than are commercial and residential land uses, military land has increasing value for habitat conservation and preservation. By itself, land on military installations is insufficient to ensure populations' long-term viability. Primary TES habitat must remain genetically connected with off-installation areas. A number of tools, "fragmentation models," which quantify the effect of habitat fragmentation on the persistence of threatened and endangered species, promise to help address the challenge of encroachment upon, and increasing need for training lands. This work reviewed a number of habitat fragmentation models and performed an in-depth investigation of one application at Fort Hood TX. This review evaluated and identified the relative strengths and weaknesses of landscape scale TES habitat fragmentation models as they relate to military installations within the continental United States.

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